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THESIS

**THE EFFECTIVE USE OF MULTIPLE UNMANNED
AERIAL VEHICLES IN SURFACE SEARCH
AND CONTROL**

by

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13. ABSTRACT (maximum 200 words)

This study analyzes the effective use of multiple unmanned aerial vehicles (UAVs) for the Navy's Surface Search and Control mission. In the future, the Navy hopes to leverage the capabilities of a family of UAVs to provide increased situational awareness in the maritime environment. This family of UAVs includes a Broad Area Maritime Surveillance (BAMS) UAV and Vertical Take-Off UAVs (VTUAVs). The concepts of operations for how these UAVs work together have yet to be determined. Questions exist about the best number of UAVs, types of UAVs, and tactics that will provide increased capabilities. Through modeling and agent-based simulation, this study explores the validity of future UAV requirements and provides insights into the effectiveness of different UAV combinations. For the scenarios modeled, the best UAV combination is BAMS plus two or three VTUAVs. However, analysis shows that small numbers of VTUAVs can perform as well without BAMS as they do with BAMS. For combinations with multiple UAVs, BAMS proves to be a valuable asset that not only reduces the number of missed classifications, but greatly improves the amount of coverage on all contacts in the maritime environment. BAMS tactics have less effect than the mere presence of BAMS itself.

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THE EFFECTIVE USE OF MULTIPLE UNMANNED AERIAL VEHICLES IN SURFACE SEARCH AND CONTROL

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ABSTRACT

This study analyzes the effective use of multiple unmanned aerial vehicles (UAVs) for the Navy's Surface Search and Control mission. In the future, the Navy hopes to leverage the capabilities of a family of UAVs to provide increased situational awareness in the maritime environment. This family of UAVs includes a Broad Area Maritime Surveillance (BAMS) UAV and Vertical Take-Off UAVs (VTUAVs). The concepts of operations for how these UAVs work together have yet to be determined. Questions exist about the best number of UAVs, types of UAVs, and tactics that will provide increased capabilities. Through modeling and agent-based simulation, this study explores the validity of future UAV requirements and provides insights into the effectiveness of different UAV combinations. For the scenarios modeled, the best UAV combination is BAMS plus two or three VTUAVs. However, analysis shows that small numbers of VTUAVs can perform as well without BAMS as they do with BAMS. For combinations with multiple UAVs, BAMS proves to be a valuable asset that not only reduces the number of missed classifications, but greatly improves the amount of coverage on all contacts in the maritime environment. BAMS tactics have less effect than the mere presence of BAMS itself.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

BAMS	Broad Area Maritime Surveillance
BDA	Battle Damage Assessment
C2	Command and Control
CCOI	Critical Contact of Interest
CFFC	Combined Fleet Forces Command
COI	Contact of Interest
CONOPS	Concept of Operations
COP	Common Operational Picture
CSG	Carrier Strike Group
EO	Electro-optical
EO/IR	Electro-optical/Infrared
ESG	Expeditionary Strike Group
FNF	Fire and Forget
GHMD	Global Hawk Maritime Demonstration
HALE	High Altitude, Long Endurance
I&W	Indications & Warning
IR	Infrared
ISAAC	Irreducible Semi-Autonomous Adaptive Combat
ISAR	Inverse Synthetic Aperture Radar
ISR	Intelligence Surveillance and Reconnaissance
JROC	Joint Requirements Oversight Council
JTF	Joint Task Force
LCS	Littoral Combat Ship
LOS	Line of Sight
LRE	Launch and Recovery Element
MANA	Map Aware Non-uniform, Automata
MCE	Mission Control Element
MIO	Maritime Interdiction Operations
MMTI	Maritime Moving Target Indicator

MNS	Mission Needs Statement
MOE	Measure of Effectiveness
MPRF	Maritime Patrol and Reconnaissance Force
MS	Maritime Surveillance
MTA	Maritime Targeting Acquisition
NAVAIR	Naval Air Systems Command
OPAREA	Operational Area
O&S	Operations and Support
OR	Operations Research
SA	Situational Awareness
SAG	Surface Action Group
SAR	Synthetic Aperture Radar
SEA-5	Systems Engineering Group
SLOCs	Sea Lines of Communication
SSC	Surface Search and Control (Surface Surveillance Coordination)
SuW	Surface Warfare
TACMEMO	Tactical Memorandum
TACON	Tactical Command
TACSITS	Tactical Situations
TCS	Tactical Control Station (for VTUAV)
TDSI	Temasek Defense Systems Institute
TSC	Tactical Support Center (for GHMD)
TSP	Travelling Salesman Problem
TTP	Tactics, Techniques and Procedures
UAVs	Unmanned Aerial Vehicles
USAF	United States Air Force
VTUAV	Vertical Take-off Unmanned Aerial Vehicles

EXECUTIVE SUMMARY

This research analyzes the effective use of multiple unmanned aerial vehicles (UAVs) for the Navy's Surface Search and Control (SSC) mission. In the future, the Navy hopes to leverage the capabilities of a family of UAVs to provide increased situational awareness in the maritime environment. This family of UAVs includes a Broad Area Maritime Surveillance (BAMS) UAV and Vertical Take-Off UAVs (VTUAVs). However, the exact concepts of operations (CONOPS) that these assets will employ have yet to be determined. Questions exist about the best number of UAVs, types of UAVs, and tactics that will provide increased capabilities. This study presents some answers to these questions through analysis of results obtained with an agent-based model.

A software program called MANA (Map Aware Non-uniform, Automata) serves as the conduit for this study's agent-based simulation. The simulation models BAMS as a high altitude, long endurance UAV with a long radar detection range. VTUAVs are modeled as "pouncers" that can birddog enemy vessels once they are classified.

Two different scenarios are modeled based upon four of the Naval Air Systems Command (NAVAIR) approved tactical situations (TACSITS) for the Navy's precursor to BAMS called Global Hawk Maritime Demonstration (GHMD) (See Appendix). The first scenario is called "Embargo" and it simulates a Maritime Interdiction Operations (MIO) mission in which an enemy force is smuggling goods. The second scenario is called "Assured Access" and it simulates a friendly force entering a gulf-like region through a

strait. Both scenarios model over 10,000 square nautical miles of coastal environment with dense shipping traffic and sparse enemy contacts.

Data are collected on almost 20,000 runs of the simulation in both scenarios, with different combinations of UAVs, friendly force tactics, and enemy force maneuvers. Friendly tactics involve a change in BAMS' movement algorithm from a traveling salesman problem (TSP) solution to a "Barrier" search along specific waypoints. Red force maneuvers involve different routing. Data from the runs allows for analysis on when, where, and how long the friendly force classifies enemy ships.

There are four primary findings in this study. Of course, each finding is in the context of the scenarios modeled.

The first two findings pertain to the most effective numbers of UAVs. For the scenarios chosen, the best combination of UAVs is the Broad Area Maritime Surveillance (BAMS) UAV and two to three Vertical Take-Off UAVs (VTUAVs). However, small numbers of VTUAVs can do just as well, if not better, when they operate without BAMS versus when they operate with BAMS. Both of these results are in terms of the lowest amount of time until first enemy classification.

The third finding deals with the most effective type of UAVs. Combinations of multiple UAVs that include BAMS tend to have advantages over those combinations without BAMS. These advantages include less average numbers of missed classifications and an increase in the proportion of time that all types of contacts are positively identified.

The fourth finding deals with the best UAV tactics to employ. The study shows that the tactics that BAMS employs do not usually make that much of a difference. This is, in large part, due to its long detection range—i.e., no matter what its search pattern is, BAMS detects all surface contacts in the operational area.

These findings lend themselves to operational recommendations about the numbers of UAVs, types of UAVs, and UAV tactics to employ in the maritime SSC environment.

In terms of numbers, investments in more UAVs are warranted, but should not be overblown. More UAVs certainly seem to provide more operational capability, but there is a point of diminishing returns at the two or three VTUAV point. A strong recommendation is to equip naval forces in scenarios similar to those modeled with enough capability that at least two VTUAVs can be operated at all times.

In terms of future UAV types, this study may or may not validate the operational requirement for a BAMS UAV. Poorer performance of combinations with BAMS and less VTUAVs diminishes the importance of BAMS as a force multiplier. However, the effectiveness of BAMS with higher numbers of VTUAVs advocates the use of BAMS. In addition, BAMS' benefits in terms of reducing the number of leakers, and providing overall coverage, may outweigh all other results. A valid recommendation is to pursue the procurement of BAMS, but to augment it with at least two other cooperative VTUAVs.

Finally, in terms of tactics, this study suggests that with respect to BAMS, tactics are less important than the presence of BAMS itself. For the most part, results with

changes in both enemy and friendly tactics seem to provide similar results. A valid recommendation is to emphasize studies with other scenarios to see if this is always the case.

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I.   INTRODUCTION

A.   PROBLEM/NAVY INTEREST

The Navy plans to take advantage of Unmanned Aerial Vehicles (UAVs) to perform many of the tasks that its manned assets perform today. As the Expanded Concept of Operations for the Navy's High Altitude Long Endurance Aircraft (HALE) states:

> The evolution of the hostile surface-to-air and air-to-air threat and their collective effectiveness against manned aircraft and satellites can generate unacceptably high attrition rates. Current systems cannot perform these missions in a timely, responsive manner in an integrated hostile air defense environment without high risk to personnel and costly systems. There is a need for a capability, which can be employed in areas where enemy air defenses have not been adequately suppressed, in heavily defended areas, in open ocean environments, and in contaminated environments.   (Navy High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle Expanded Concept of Operations, Draft 4, 2004, hereafter referred to as HALE CONOPS, 2004)

Although the complete replacement of manned systems with unmanned systems is an unreasonable expectation for the near future (SEA-5, 2004), the augmentation of unmanned systems into the Fleet is forthcoming. This is evidenced by the fact that future configurations for the Littoral Combat Ship (LCS) may substitute helicopters with Vertical Take-off UAVs (VTUAVs) (Burgess, 2004). The Navy has also shown interest in the development of a Broad Area Maritime Surveillance (BAMS) UAV in order to replace aging land-based maritime search platforms. Within the broader

context of the Surface Search and Control (SSC) mission, initial Navy doctrine also recommends roles for these capabilities in focused search and cooperative identification tasking (TM 3-22-5-SW, 2004).

The Fleet is the stakeholder for this research, and it has many questions about UAV implementation. There are questions about what "speed, altitudes, sensor package and line of sight" are most effective. As well as "what kind of footprint can we expect and are we talking solo, section (two), or division (four) ops?" (Olivarez, 2004) The U.S. Navy's THIRD Fleet has asked, "Can we get a sampling of the Concepts of Operation (CONOPS) that describe how we'll employ UAVs in a maritime environment?" (Olivarez, 2004).

Thorough exploration of these issues can answer questions about UAV supportability for the Navy's vision of the future (Clark, 2004). It is one question to ask about the proper mix of UAVs in order to be effective. It is another to see what tactics will ensure that effectiveness. Currently, such tactics do not exist.

B. A PREVIOUS STUDY

To date, study into the tactics for multiple UAV operations has been limited. In a focused study on tactics and optimized search patterns for UAVs, the Operations Research (OR) Team of the Temasek Defense Systems Institute (TDSI) collaborated with the Systems Engineering and Analysis Team 5 (SEA-5) in an attempt to analyze tactics for multiple UAVs. Using high-level UAV definitions and sensor capabilities, the study compares sensor capabilities, tactics, and numbers of

UAVs in a given scenario. Specifically, it focuses on the detection and identification missions. The study points out that:

> . . . The search and identification problem is easier if it is assumed that the picture of the search area (provided by the P-3 or other high altitude orbiting asset) is always available. If such an asset exists, then the UAV flight path problem essentially resolves itself into a "traveling salesman problem" . . . In this problem, the salesman is given a finite number of cities along with the cost of travel between each pair of them. The challenge is for the salesman to find the cheapest way to visit all cities and return to his or her starting point. This type of problem can be solved with optimization techniques such as linear programming. (Temasek Defense Systems Institute, 2004)

As a result, the study explores the case with no high altitude orbiting asset available. The study concludes that UAV tactics do matter. That is, the number of UAVs and the patterns that UAVs fly have a direct effect on the coverage area and probability of detection of contacts of interest (Temasek Defense Systems Institute, 2004).

This thesis examines multiple UAV operations as well, but it differs from the TDSI study in that it also examines the case where information is passed from a high altitude asset to smaller UAVs, which act more as "pouncers." Although the "traveling salesman problem" mentioned above does apply to this situation, it is of limited use. It takes time for the high orbiting asset to detect all targets and to determine which targets are of critical interest. "Pouncer" UAVs must also spend a certain amount of time at each contact of interest before they can move on to other contacts. This thesis also reviews the case in

which there is a lack of "pouncers" and only the high altitude asset is available.

C. KEY ISSUES AND CONCEPTS

It is possible to decompose the surface search UAV problem into two separate areas: detection and identification. The distinction between detection and identification is important because these tasks inherently involve many different aspects of surface search. Although both missions are related, each presents its own difficulties because they compete for resources, consume time, and require different assets (Temasek Defense Systems Institute, 2004). Also, an asset may not commence the identification mission until detection has been accomplished organically or by some other asset.

Traditionally, the Navy handles the missions of detection and identification with multiple assets under a broad mission called Surface Search and Control (SSC). At sea, surface detections are often made by long-range, land-based, maritime search aircraft such as the P-3C Orion. These aircraft extend the Fleet's surface picture and provide an extended aerial view of all surface contacts. Shipboard watch-standers use the information from these assets to maintain the Recognized Maritime Picture (RMP).

The RMP is "about maintaining an unambiguous and timely database of the position and identification of all tracks, both warship and merchant, and being able to distinguish good or cleared ships from the adversary, unchallenged, suspect, or blockade running ships" (Germain, 1997). The RMP helps to provide commanders with

a Common Operational Picture (COP). The COP allows "decision makers [to] have a more effective means of evaluating tactical situations through this common display of forces. This enhances the Joint Task Force (JTF) Commander's ability to effectively exercise command and control of his battle-space and enables synchronized execution of forces" (SPAWAR, 1995).

If more information is needed on a certain contact in order to update the RMP and the COP, then the P-3C investigates that contact further, or perhaps another locally deployed asset is tasked to obtain more information. These deployed assets may include helicopters, such as the SH-60B, other jet aircraft, or surface ships.

In effect, commanders employ one long-endurance asset as the detection agent and other assets as "pouncers" in order to accomplish identifications. With limited assets, contacts, or compressed timelines, a single asset often performs both of these roles. In other words, the SH-60B that detects three surface contacts is the same one that investigates and identifies each of these three contacts in order to properly identify them. Whatever the case may be, all SSC assets work together to accomplish both the detection and identification tasking.

The Navy sees the BAMS UAV as an eventual replacement for the long-range P-3C aircraft in the SSC mission since...

> The land-based, manned airborne platforms that perform the broad area maritime and littoral Intelligence, Surveillance, and Reconnaissance (ISR) functions today are reaching the end of their service life and are facing possible

reduced flight operations and subsequent near-term retirement. Airframe life issues, declining availability rates, high Operations and Support (O&S) costs and limited system growth capacity plague legacy MPRF [Maritime Patrol and Reconnaissance Force] aircraft (P-3C). (Operational Requirements Document for Broad Area Maritime Surveillance (BAMS) Unmanned Aerial Vehicle, Draft version 3.0, DEC 03.

In addition, the Chairman of the Joint Requirements Oversight Council (JROC) signed a validated Mission Needs Statement (MNS) for a "Close Range and Long Endurance Reconnaissance, Surveillance, and Target Acquisition Capability" (JROC MNS 003-90, 1990).

To augment the JROC MNS, the Navy has decided to increase its emphasis on UAVs with "both a short-term plan to capitalize on existing systems and a longer-term plan to develop a family of unmanned vehicles" (HALE CONOPS, 2004). The short-term plan is called Global Hawk Maritime Demonstration (GHMD) and it is currently supervised by the Naval Air Systems Command GHMD Test and Experimentation Design Division, Integrated Systems Evaluation, Experimentation and Test Department. This program office describes the Navy's UAV plan as a two-phased process.

Phase I will be procurement of an Air Force production line Global Hawk system which will have modifications to the existing sensor package to make it more compatible with a maritime environment. A system will consist of two air vehicles with payloads, a launch and recovery element and mission control element. The system will be used primarily for experimentation and CONOPS development leading to Phase II. Phase II (now called BAMS UAV) will leverage from the Broad Area Maritime and Littoral Armed Intelligence, Surveillance, and Reconnaissance Mission Needs Statement and Analysis of

Alternatives to competitively acquire high altitude long endurance vehicles with robust and fully capable maritime sensor payloads. The thrust of BAMS UAV will be towards developing sensor/payload capability or identifying existing sensor/payloads capable of performing BAMS missions. (HALE CONOPS, 2004)

GHMD will be a system that "leverages United States Air Force (USAF) contracts to expeditiously procure a robust UAV system" (NAVAIR 5.1.1, 2004). It will:

- Provide Navy Concept of Operations (CONOPS), Tactics Techniques and Procedures (TTP), and Experimentation for 24/7 ISR System
- Rapidly insert Persistent Intelligence Surveillance and Reconnaissance (ISR) UAV capability to the Navy
- Be an Enduring Test Bed
- Develop/Gain Fleet user community advocacy
- Address Naval transformational Roadmap initiatives (e.g., Sea Trial) (NAVAIR 5.1.1, 2004)

In pursuit of the aforementioned longer-term plan to develop a family of unmanned vehicles, the Navy expects to equip the new Littoral Combat Ship (LCS) with VTUAVs, an example of which is the Fire Scout. The RQ-8A Fire Scout will augment the Fleet in order to facilitate the following missions:

- Surface Search and Control (SSC)
- Birddog/tattletale operations
- Maritime Interdiction Operations (MIO)
- Targeting
- Battle Damage Assessment (BDA)

(Klingbeil, July 2004)

In other words, stakeholders desire a VTUAV to act as the "pouncer" aircraft that can identify and closely monitor surface contacts of higher interest.

Together, the two types of UAVs——BAMS and VTUAVs——are expected to work together to help accomplish the detection and identification missions for the Navy of tomorrow. However, the exact CONOPS and specific tactics that these assets will employ have yet to be determined. Questions about these CONOPS specifically include the number of UAVs required to complete the identification mission, tactical dependencies on BAMS and VTUAV availability, and tactics selection. This thesis addresses these issues. It analyzes the performance characteristics of both the BAMS and VTUAVs to gain insight into whether and how they should work together in the SSC role, in a variety of scenarios.

The number of UAVs needed to complete the identification mission is dependent upon the size of the search area and the sweep-width of UAV sensors (Washburn, 2002). However, operations with increased numbers of UAVs may be more complicated with an increased requirement for airspace separation and coordination. There may also be some point of "diminishing returns" when the marginal benefits of adding another UAV, in terms of the time from detection to identification or the proportion of time in which all contacts are positively identified, are outweighed by the cost of an additional asset.

The types of UAVs available also directly affect UAV tactics. In the absence of VTUAVs, BAMS must spend more of its time on each unidentified contact in order to positively identify and monitor it. Similarly, in the absence of the BAMS UAV, VTUAVs need to spend more time on

the detection problem in order to maintain the RMP. Under ideal conditions, both types of UAVs work together to accomplish both the detection and identification missions. But realistically, both types of assets may not always be available, or may be available in varying numbers.

This analysis studies and compares three specific force packages of UAVs. The first set requires the BAMS UAV to operate without the presence of any VTUAVs. Although the BAMS UAV is able to fly at altitude and "see" all surface contacts with its long-range radar, in the absence of other UAVs, it is necessary for BAMS to spend more time at each surface contact in order to properly identify it with shorter-range electro-optical/infrared (EO/IR) sensors. The second set requires the VTUAVs to operate without the presence of the BAMS UAV. Without the advantage of the overall surface picture, the VTUAVs need to explore the surface picture without any outside information. Multiple VTUAVs first need to detect surface contacts and then identify them. Without the overall picture, the VTUAVs should not be as effective.

The third set requires BAMS and the VTUAVs to work together in order to complete the detection and identification missions. Here, the greatest level of efficiency is expected as the VTUAVs benefit from the overall surface picture provided by the BAMS UAV. The BAMS UAV also benefits in that it does not have to spend as much time identifying and monitoring surface contacts since the VTUAVs can now be vectored in to accomplish these missions.

Tactics selection is another focus of this study. Specific flight paths that UAVs follow will affect force

performance.   More specifically, mission profile affects the time from detection to identification. Whether the UAV simply flies a pattern based upon a traveling salesman type of algorithm, or it flies some sort of barrier search along the expected route of critical contacts of interest influences the efficiency of its patrol.   This study analyzes which tactics work best in different scenarios.

Each of these areas, the number of UAVs, the types of UAVs available, and the tactics for available UAVs are of critical interest to the CONOPS for the Navy of tomorrow. This thesis analyzes these factors to determine which aspects of them are most important.

Chapter Two provides more information on the UAVs themselves, the scenarios explored in this study, and performance measures. Chapter Three describes how these UAVs and scenarios are implemented in agent-based software, in order to facilitate the experiment.   Results are described in Chapter Four.   Finally, Chapter Five summarizes the overall conclusions to be drawn from this study.

II. BACKGROUND

A. OVERVIEW

Chapter Two provides background for the modeling used to investigate the types and numbers of unmanned aerial vehicles (UAVs) that work best, as well as what UAV tactics are most effective. After fully describing the capabilities and characteristics of the UAVs themselves, it describes the operational scenarios in which these UAVs are employed, as well as their measures of effectiveness. Finally, the chapter discusses the agent-based model used for analysis.

B. UAV CHARACTERISTICS

1. BAMS

The Broad Area Maritime Search (BAMS) UAV is the first type of UAV modeled in this study. Although no specific "BAMS" UAV currently exists in the Navy today, the Global Hawk Maritime Demonstration (GHMD) UAV has been procured as a stepping stone toward such development. GHMD "will be utilized to support tactics, techniques, and procedures (TTP) and CONOPS (concepts of operations) development in support of the Navy's future high altitude, long endurance (HALE) UAV program," (Combined Fleet Forces Command (CFFC), 2004). This is the naval variant of the Global Hawk UAV currently employed by the U.S. Air Force.

GHMD is designed to "employ Radar, electro-optical (EO) and infrared (IR) sensor packages worldwide." Sponsors expect it to "locate, identify, track, and observe/monitor friendly, enemy, non-friendly, and

non-aligned forces," to improve situational awareness for decision makers (HALE CONOPS, 2004).

Essentially, GHMD (Figure 1) is a software-modified version of the U.S. Air Force Global Hawk. The GHMD CONOPS states that:

> These software modifications allow the radar to do the following modes: Maritime Surveillance (MS) mode, Maritime Targeting Acquisition (MTA) mode, Inverse Synthetic Aperture Radar (ISAR) mode . . . The ISAR capability substantially differs from the USAF SAR (synthetic aperture radar) in that it can also detect moving objects on the ocean, vice only stationary objects and some moving objects on land. (GHMD CONOPS, 2004)

Figure 1: Global Hawk Maritime Demonstration

This study focuses on UAV movement and contact detection and identification. Therefore, the speed, range, and endurance of the GHMD airframe, as well as the ranges of the GHMD (Maritime Surveillance (MS)) radar and electro-optical/infrared (EO/IR) sensors, are important. A brief summary of some performance parameters obtained from NAVAIR are listed in Table 1.

Endurance	31 hours
Combat Radar	9,500 nautical miles
True Air Speed	340 knots
Radar Range	20-200 kilometers
EO/IR Range	28 kilometers

Table 1: GHMD Characteristics (NAVAIR 5.1.1, 2004)

GHMD is a high altitude, orbiting asset. The unmanned aircraft typically flies at 65,000 feet in order to stay well out of the reach of most conventional weapons. Although this is advantageous for survivability, it also means that GHMD sensors are more susceptible to obscuration by high-level cloud layers than aircraft operating at lower altitudes.

GHMD also consists of a Mission Control Element (MCE) and a Launch and Recovery Element (LRE). The LRE contains systems and equipment necessary to launch and recover the aircraft from a land base. Typically, GHMD takes advantage of its long endurance and time on station to take off from these land bases at great distances from the battle space. Outside of the launch and recovery phases, GHMD is controlled by operators in the MCE. MCE operators then relay information from the GHMD to the Tactical Support Center (TSC) on board ship through various communication networks (GHMD CONOPS, 2004).

2.   **VTUAVs**

Vertical Take-Off Unmanned Aerial Vehicles (VTUAVs) are the other type of unmanned vehicle modeled in this study. The Navy's prototype VTUAV, the RQ-8A, is called the Fire Scout. The Fire Scout is essentially an unmanned helicopter that is capable of "autonomous operations from all air capable ships" (Klingbeil, 2004).

The Fire Scout (see Figure 2) is designed to perform the following Surface Warfare (SuW) missions:

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Surface Search and Control (SSC), Birddog/Tattletale Operations, Maritime Interdiction Operations (MIO) Support, Targeting, and Battle Damage Assessment (BDA) (Klingbeil, 2004). When it comes to these missions, operators employ the RQ-8A's EO/IR sensor. For the purposes of this study, the maximum effective range of this sensor is considered to be on the order of the GHMD EO/IR sensor, namely 28 kilometers. Of course, the effective range is dependent upon altitude and weather conditions, but 28 kilometers, roughly 15 nautical miles, is a good maximum value since it is accepted for planning purposes as the estimated maximum for EO/IR sensors presented in the U.S. Navy's Unmanned Vehicle (UV) Maritime Integration Tactical Memorandum (TACMEMO) (TM 3-22-5-SW, 2004).

Figure 2: RQ-8A Fire Scout VTUAV

The basic performance parameters of the Fire Scout airframe are listed in Table 2.

Endurance	6+ hours
Tactical Range	110 nautical miles
True Air Speed	0-100 knots
EO/IR Range	28 kilometers

Table 2: VTUAV Characteristics (Klingbeil, 2004)

The Fire Scout VTUAV is an example of the "pouncer" type of asset mentioned in Chapter One. VTUAVs can "help sort out the surface picture and enable situational awareness because it can provide EO/IR imaging," (Klingbeil, 2004). In general, VTUAVs are proposed to launch from smaller air capable ships such as the Littoral Combat Ship (LCS). They are then controlled from the ship by watch standers and a Tactical Control Station (TCS) that processes information received from the VTUAV.

UAV technology has advanced to the point where the VTUAV can even be launched, controlled, and recovered via a TCS stationed on board an airborne P-3C Orion aircraft (Hatcher, 2004). This indicates that UAV technology is safely becoming more autonomous. Considering these advances, it is reasonable to expect that flights of multiple UAVs from multiple platforms will become a reality in the future.

C.   SCENARIOS

Specific scenarios are required in order to study the Navy's view of a future involving both types of the UAVs mentioned above. For this study, two scenarios are adopted. These scenarios are broad enough to represent critical operational issues associated with UAV use in maritime missions.

The two scenarios are based upon four of the Naval Air Systems Command (NAVAIR) approved tactical

situations (TACSITS) for GHMD (See Appendix). Scenario I is called "Embargo" and it combines the Embargo and SuW TACSITS. Scenario II is called "Assured Access" and it combines the Indications & Warning (I&W) and Intelligence, Surveillance, and Reconnaissance (ISR) TACSITS. These TACSIT combinations are based upon the use-cases (i.e., system processes) for each scenario. Since the Embargo and SuW TACSITS provide for tactical control (TACON) of the UAV to rest with the Tactical Support Center (TSC) or Surface Action Group (SAG) Commander, Scenario I depicts a Blue SAG. Scenario I is also one that is commonly encountered by SAGs, namely, Maritime Interdiction Operations (MIO).

Since the I&W and ISR TACSITS provide for TACON to rest with the Expeditionary Strike Group (ESG) or Carrier Strike Group (CSG) Commander, Scenario II depicts the transit of a Blue CSG or ESG. The scenario is one that is commonly encountered by CSG/ESG forces, namely, straits passage.

Each scenario is introduced with a snapshot of the area as it is eventually depicted in the simulation software. These areas are selected for their proximity to Naval test facilities on the East and West Coast of the United States. They are conceptual extensions of real geographical locations to support the operational environment. Each diagram is followed by a short summary of the scenario, along with details in terms of background, initial conditions, operating conditions, processes, constraints, and measures of effectiveness (MOEs).

The MOEs correspond to three UAV objectives outlined in the U.S. Navy TACMEMO on the "Integration of

Unmanned Vehicles into Maritime Missions." These objectives are: the minimization of the time between detection and identification, the minimization of uncertainty regarding contact position and movement, and the maximization of collection of priority intelligence requirements (TM 3-22-5-SW, 2004). For this thesis, these objectives translate into the following MOEs:

1) Time between detection and positive identification.

2) Location of first enemy detection.

3) Proportion of time that each contact is positively identified.

The time between detection and identification directly influences Blue force safety. If Red forces can be identified quickly, then the Blue force has more time to safely address a potentially hostile situation. However, the location of identification is also important since it influences Blue force tactics. If Red forces are first identified along the coast, then perhaps the Blue forces should spend more time in coastal areas in the future.

The proportion of time that each contact is positively identified measures how complete the maritime picture may be at any given time. This MOE also corresponds to the collection management MOE described in the Navy UAV TACMEMO which refers to "tactical reconnaissance" or the "percentage of vital area tracks positively identified" (TM 3-22-5-SW, 2004).

Each MOE is also described more fully after each scenario summary.

1. Embargo Scenario

a. Summary

In this scenario (shown in Figure 3), the Red force consists of two surface vessels. These vessels attempt to smuggle their goods to Country B without being detected by the Blue force. One Red force ship hides among the numerous fishing and merchant vessels in the area, attempting to cross the open ocean directly to Country B. The other Red force ship hugs the territorial waters, exploiting clutter from the sea-shore interface, as well as the fact that Blue forces cannot pursue there, depending upon rules of engagement.
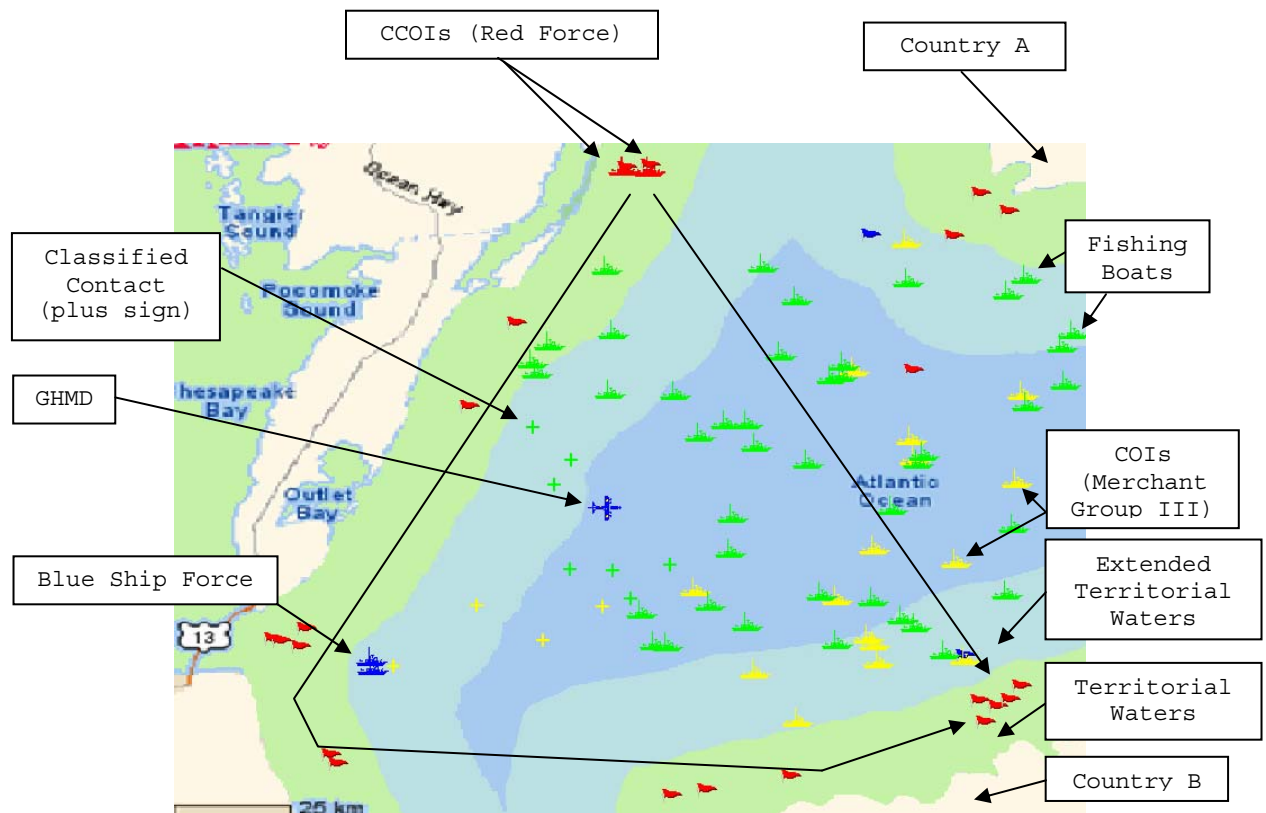
Figure 3: Embargo Scenario

BAMS arrives from the southwest corner of the area (near the entrance to the Chesapeake Bay). The UAV

uses its broad area search maritime surveillance (MS) radar to detect all contacts within the area. These contacts are classified as unknowns and the UAV flies toward each one for classification and identification with its shorter-range sensors. When the UAV encounters a critical contact of interest (CCOI), it devotes more time to that particular contact in order to gather even more information (electronic transmissions, intelligence, configuration, etc.) and maintain surveillance. The UAV does not spend as much time monitoring merchant ships or fishing vessels. If other VTUAVs are available in this scenario, then they may be vectored to help BAMS with the identification process.

b.   Scenario Background and Initial Conditions

This scenario takes place off of the Chesapeake Bay in order to simulate the operations near Patuxent River. Two simulated countries exist in the northeastern and southeastern parts of the operational area. The area considered is greater than 10,000 square nautical miles.

Combining the NAVAIR Embargo and SuW TACSITS listed in the Appendix, analysis using this scenario focuses on the exploitation of Sea Lines of Communication (SLOCs) by the Red force. BAMS is tasked to help provide information that allows the Blue force SAG to maintain a COP.

BAMS launches from Patuxent River and flies toward the southwest portion of the operational area. Blue force ships also transit into the area from the southwest. The Red force ships start in the northwest near the coast. The goal of the Red force is to smuggle their goods to the southeastern section of the operational area (Country B).

BAMS provides the position of all surface contacts for the COP and then employs its sensors to enable operators to individually classify and identify each one of the contacts that it finds. VTUAVs, when available, are also employed to help with the identification process. This information supports the COP for the SAG Commander.

c.   *Operating Conditions*

Weather conditions and sea state can make classification and identification of all contacts with EO/IR sensors more difficult. Cloudy conditions mean that UAVs need to get closer to contacts (or spend more time over certain targets while the target moves in and out of cloud coverage) in order to gain higher confidence in the level of identification that it provides. In some cases, clouds obscure EO/IR sensors and prevent positive identification, or at least delay the process.

Merchant traffic in and around the shipping lanes and fishing vessels throughout the area also create more contacts for UAVs to investigate and may serve as hiding places for Red forces. Here again, the requirement for operators to sort through all the contact data that UAVs provide also slows down the Blue force's ability to make positive identifications.

d.   *Processes*

BAMS first uses its broad area surface search MS radar to locate all surface contacts in the region. Then it maneuvers to the closest target and continues to investigate additional targets. Several methods may be used for this investigation. For example, BAMS' path could be determined by a continuously modified "traveling salesman problem," in which the UAV needs to constantly

calculate the best way to visit all its "customers" or unidentified contacts. Alternatively, it could conduct a barrier search across the shipping lanes or along the SLOCs, anticipating more Red force interest. If available, VTUAVs are also vectored in toward the contacts that BAMS detects in order to identify and track enemy contacts.

e. Constraints

Although BAMS is not extremely limited by its speed or sensor range (340 knots and 200 kilometers, respectively), it is required to revisit each contact after a certain period of time in order to update track and surveillance data. Revisit intervals are shorter for more CCOIs.

VTUAVs are also limited in that they are slower and depend primarily on their shorter EO/IR sensor ranges (90 knots cruise and 28 kilometers, respectively). As the aforementioned "pouncer-type" asset, VTUAVs stay on top of enemy contacts for longer periods than BAMS.

All UAVs are also constrained in that they can only operate in international airspace.

f. Measures of Effectiveness

(1) Time between Detection and Positive Identification. In the Embargo scenario, the time from detection to identification is a measure of resource utilization. While it may be possible to positively identify all contacts in a certain operational area if the number of assets or the amount of time were unlimited, such a possibility is unrealistic when resource constraints, maintenance down time, and system reliability are taken into account. To minimize the chance that a CCOI might slip through an area of interest, and maximize resource

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utilization, it is desirable to minimize the time from detection to positive identification.

(2) Location of First Enemy Classification. In the Embargo scenario, the location of first classification of CCOIs plays a critical role for Blue force operations planning. Depending on the location of the CCOIs, Blue forces can better determine Red force tactics and the most efficient interdiction plan. For example, if the enemy is first classified along the shipping routes, then some sort of barrier patrol across the lane may be warranted for future operations. If the enemy manages to hug the coastline and maneuver undetected until crossing the open ocean in the south, then Blue forces may want to search the coastline earlier.

(3) Proportion of Time that each Contact is Positively Identified. Since smugglers may disguise themselves as merchant ships or fishing vessels, monitoring CCOIs is an important function. In the Embargo scenario, perceptions about contacts of interest often change rapidly as the situation is "often interrupted by high-priority, quickly changing intelligence and tasking," (Gillio, 2002). Smugglers use "vessels of different sizes and descriptions . . . some of these boats are blacked out, while others display a confusing array of deck and navigation lights," (Collins, 2001). Hence, the proportion of time that each contact is positively identified is a direct contributor toward mission success.

2. Assured Access Scenario

a. *Summary*

In this scenario (shown in Figure 4), Blue forces require ISR support as they prepare to transit through an international strait. This support includes knowledge of the presence and activity of all Red forces in the area. BAMS approaches from the northwest after transit from an air base. The UAV passes through the strait and uses its broad area search radar to detect all contacts within the area. The UAV uses its Maritime Surveillance (MS) radar and proceeds toward each contact for identification and classification with shorter-range EO/IR sensors. If the UAV encounters a Critical Contact of Interest (CCOI), it devotes more sensor time to that particular contact in order to gather information (electronic emissions, intelligence, configuration, etc.) and maintain surveillance. The UAV does not spend as much time monitoring merchant vessels or fishing vessels. If other VTUAVs are available in this scenario, then they may be vectored to help BAMS with the identification process. In this particular scenario, the Red forces consist of a limited number of surface vessels. These vessels monitor maritime traffic near the strait, as well as near their own coastlines.
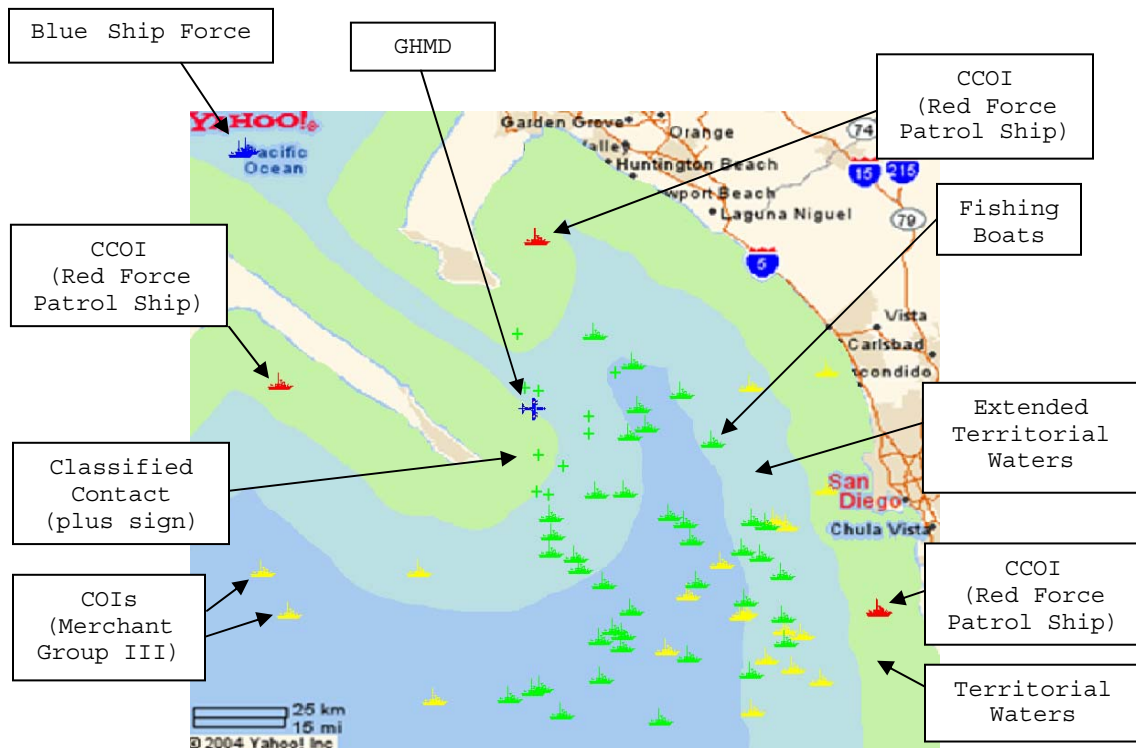
Figure 4: Assured Access Scenario (best viewed in color)

b. Scenario Background and Initial Conditions

This scenario takes place in the Southern California operational area in order to support operations near Point Mugu, China Lake, and San Diego. San Clemente Island and Catalina Island form a constructive strait. This strait is depicted as the entrance into an area similar to the Persian Gulf. The area is greater than 10,000 square nautical miles.

This scenario combines I&W and ISR TACSITS with a focus on surveillance. Tensions are high and the Red force is potentially hostile. The goal is for the Blue force to search the area, locate and identify all Red forces in the area. BAMS is tasked to support development of a highly accurate and continuous Common Operational Picture (COP) for the Blue force.

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BAMS launches from Point Mugu, China Lake, or San Diego and flies toward the northwest portion of the operational area. Any available VTUAVs and Blue force ships will also enter the notional strait from the northwest beyond San Clemente and Catalina Islands. Red force ships start out to the south of both islands and along the coast. The goal of the Red force is to actively target the Blue force or prevent the Blue force from asserting maritime dominance in the region.

BAMS provides the position of all surface contacts for the COP and then employs its sensors to enable operators to identify and classify each one of the contacts that it finds. VTUAVs, if available, are also employed to help with the identification process. This information supports the COP for the CSG/ESG Commander.

c.   *Operating Conditions*

As with scenario I, weather conditions and sea state can make classification and identification of contacts more difficult. Cloudy conditions mean that UAVs need to get closer to contacts (or spend more time over certain targets while the target moves in and out of cloud coverage) in order to gain higher confidence in the level of identification that it provides. In some cases, clouds obscure EO/IR sensors and prevent positive identification, or at least delay the process.

Merchant traffic in and around the shipping lanes and fishing vessels throughout the area also create more contacts for UAVs to investigate, and may serve as hiding places for Red forces. The requirement for operators to sort through all the contact data that the UAVs provide

also slows down the Blue force ability to make positive identifications.

d.   Processes

BAMS first uses its broad area surface search MS radar to locate all surface contacts in the region. Then BAMS maneuvers to the closest target and continues to investigate additional targets. Several methods may be used for this investigation. For example, BAMS' path could be determined by a continuously modified "traveling salesman problem," in which the UAV needs to constantly calculate the best way to visit all its "customers" or unidentified contacts. Another option is to have BAMS conduct a barrier search ahead of the Blue force, or focus its attention on the shipping lanes. If available, VTUAVs are also vectored in toward the contacts that BAMS detects in order to identify and track enemy contacts.

e.   Constraints

As in scenario I, although BAMS is not extremely limited by its speed or sensor range (340 knots and 200 kilometers respectively), it is constrained by the requirement to revisit each contact after a certain period of time in order to update track and surveillance data. Revisit intervals are shorter for CCOIs.

VTUAVs are constrained in that they are slower and depend primarily on their shorter EO/IR sensor ranges (90 knots cruise and 28 kilometers, respectively). As the aforementioned "pouncer-type" asset, VTUAVs are also required to stay on top of enemy contacts for longer periods than BAMS.

All UAVs are also constrained in that they can only operate in international airspace.

f. Measures of Effectiveness

(1) **Time Between Detection and Positive Identification.** In the Assured Access scenario, the time between detection to positive identification is a critical factor in the Blue force's ability to continue onward through the strait to reach the objective at a designated time. CSGs and ESGs routinely transit straits in order to establish presence or relieve the Battle Group that is currently on station. Any delay in the positive identification of all contacts in the threat environment increases transit time and susceptibility to attack.

(2) **Location of First Enemy Classification.** The location of the enemy when it is first classified is important in the Assured Access scenario since it dictates whether or not safe transit of the strait is immediately possible. If the enemy is not classified until the Blue force is already in or through the strait, or if the Red force is not classified until it has maneuvered into a position where it can seal off the strait, then the Blue force may be subject to attack while in a restricted area of operations. Ideally, the Blue force would detect the enemy presence well before entering the narrower body of water.

(3) **Proportion of Time that each Contact is Positively Identified.** Clearly it is not enough to simply detect the presence of potentially hostile contacts. Since potentially hostile contacts may often disguise themselves as normal merchant or fishing vessels, or pose as some sort of asymmetric threat with hidden explosives, all contacts must be monitored to ensure safe passage and freedom of navigation at all times. Under ideal conditions, all

contacts in the given area of operations would be positively identified and monitored for threat level, all of the time.

D.   MODEL SELECTION AND JUSTIFICATION

Operations Analysts implement different tools to answer different operational questions. In broad terms, these tools include analytical methods and simulation. Analytical methods include such techniques as linear programming, decision analysis, Markov chain analysis, and queueing theory. Simulation "involves using a computer to imitate the operation of an entire process or system [repeatedly] to generate a profile of the possible outcomes," (Hillier and Lieberman, 2001).

Both of these broad categories (analytical methods and simulation) have their advantages, but simulation is more applicable to this study. Analytical methods are advantageous because they can be more precise; "these methods are well suited for doing preliminary analysis, for examining cause-and-effect relationships, for doing rough optimization, and for conducting sensitivity analysis." But simulation is often more appropriate. For example,

> when the mathematical model for the analytical method does not capture all the important features of the stochastic system, simulation is well suited for incorporating all these features and then obtaining detailed information about the measures of performance of the few leading candidates for the final system configuration. (Hillier and Lieberman, 2001)

For the current study, it would be difficult for analytical methods to "capture all the important features of the

stochastic system." To name only a few, these stochastic features include: the varying start position of all surface contacts in the maritime environment, the probabilities of detection and identification, weather and atmospheric conditions, and the probability that a contact will be in a certain position, at a certain time, based upon rules for BAMS and VTUAV movement, as well as Blue and Red force tactics. Some of the other variables involved in the analysis of UAV operations and the determination of UAV flight paths are listed in Tables 3 and 4.

MOE	Applicable Variables
Time Between Detection and Identification	-UAV flight profiles -P(Detection) -P(Identification) -Weather, environmental effects
Location of Initial Enemy Classification	-UAV flight profiles -Contact maneuverability -Sea state
Proportion of Time Positively Identified	-Duration of time that UAV is required to orbit contact -Revisitation rate requirement -Threat environment -UAV availability

Table 3: Some of the variables involved in UAV MOE analysis

UAV flight paths are dependent upon . . .	-Weather (barometric altimeter setting, air density, thermo-clines, cloud layers, turbulence, moisture, etc.) -Aircraft reliability -Aircraft schedule -Traffic avoidance with other aircraft/UAVs -Operator inputs -Operator crew rest

Table 4: Some of the variables involved with UAV flight profiles

The amount of these often unpredictable and indefinable variable values simply makes analytical methods too difficult. Simulation, on the other hand, is readily feasible and appropriate for this situation.

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Simulation also facilitates a comprehensive look into many different aspects of UAV operations. The number of UAVs employed in a given scenario, and types of tactics they employ, can be easily varied. The results of these variations can also be evaluated over a number of iterations. Such results would require a very complex analytical model or an inordinate amount of time and money for real-life testing if simulation could not be employed.

Although it is unrealistic to model multiple UAV operations exactly, simulation can provide real insights. As George Box states, "all models are wrong, some are useful," and this study is no exception (Box, 1979). In real life, UAV flight paths are extremely dependent on factors such as their operators, the environment, and system reliability. However, we can generalize their movement and characteristics as realistically as possible to gain insight.

In this study, agent-based modeling and stochastic methods are used to model these UAV characteristics. Agent-based models provide a flexible format that allows multiple iterations of different scenarios. In this type of simulation, agents are given certain characteristics and behaviors within a defined scenario. As the simulation progresses, agents interact with each other and their environment according to these characteristics. The end result is that these interactions may be examined over many runs, while certain conditions are varied. After this process, the effects of the different conditions and agent personalities may be examined in order to gain insight into

those variations that are more important and require further exploration.

Dr. Andy Illachinski, developer of one of the first agent-based models called Irreducible Semi-Autonomous Adaptive Combat (ISAAC), states that...

> ...The idea is to develop a tool that provides insight into, and aids the exploration of, the fundamental behavioral tradeoffs involved among a large number of notional variables.
> ...ISAAC consists of a discrete heterogeneous set of spatially distributed individual agents (i.e., combatants), each of which has its own characteristics, properties, and rules of behavior. These properties can also change (i.e., adapt) as an individual agent evolves in time. (Illachinski, 2000)

A software program similar to ISAAC, called MANA (Map Aware Non-uniform, Automata) serves as the conduit for this study's agent-based simulation (Chapter Three contains the implementation details). MANA is "designed for use as a scenario-exploring model...intended to address a broad range of problems," (Galligan, 2004). It is well suited for this UAV study in that it facilitates exploration into the areas of "situational awareness (SA), command and control (C2), and the informational edge that enhanced sensors provide," (Galligan, 2004).

To explore the problems introduced in Chapter One, both BAMS UAVs and VTUAVs are modeled as agents with different characteristics in MANA. These agents attempt to locate and identify enemy surface contact agents that must be distinguished from friendly surface contact agents. All of these interactions occur in an environment that simulates the two scenarios described earlier.

The use of MANA is beneficial because it allows the user to easily activate or deactivate certain agents within a scenario. This quality is very attractive since UAV operations are complex. In the absence of VTUAVs, BAMS spends more time on each unidentified agent in order to identify it. In the absence of the BAMS UAV, the VTUAVs spend more time on the detection problem in order to maintain the whole surface picture.

Under ideal conditions, both types of UAVs work together to accomplish both the detection and identification missions. The reality is that both assets may not always be available, or may be available in varying numbers. Through the activation of different agents among different scenarios, MANA enables simulation of these variations to gather results over many different configurations.

MANA is based upon two key ideas:

- The behavior of the entities within a combat model (both friend and foe) is a critical component of the analysis of the possible outcomes.

- Highly detailed models for determining force mixes and combat effectiveness may not be an efficient approach. (Galligan, 2004)

Since both Blue and Red forces in the UAV scenarios depicted earlier in this chapter can be modeled as agents with certain behaviors, coupled with the fact that it is nearly impossible to model all of the intricacies involved with multiple UAV flight operations, MANA is an appropriate tool for this study.

III.   MODEL IMPLEMENTATION AND EXPERIMENTS

This chapter describes how the unmanned aerial vehicles (UAVs) and scenarios described in Chapters One and Two are developed into an experiment using the agent-based modeling software, MANA. First, the chapter provides a general overview of the model and discusses some creative modeling techniques. A detailed discussion about the battlefield and agent settings themselves follows. This section covers settings in MANA that do not otherwise remain at their default values. Then, the experimental set-up itself is discussed along with the specific Red force movement and Blue force tactics evaluated in this study. This section also provides background for an additional experiment regarding weather effects.

This thesis uses version 3.0.37 of MANA, the latest version available. All details of the model development and the final model itself are available from the author or advisors and more information on MANA functionality is found in the MANA user's manual (Galligan, 2004).

A.   GENERAL OVERVIEW OF MODEL

The goal of the Blue force in this simulation is to support development and maintenance of the Common Operational Picture (COP) by positively identifying all contacts in the operational area, principally by use of its UAVs. If the Broad Area Maritime Surveillance (BAMS) UAV is available, it detects all contacts with its radar's large detection range and then proceeds to identify each

contact individually, or with the help of any available Vertical Take-Off UAVs (VTUAVs).

To achieve this behavior in MANA, all entities are modeled as agents in different squads with different personalities or movement propensities. All UAVs start out as agents with a propensity to move toward unidentified contacts, and a higher propensity to move toward enemy contacts. Depending on Blue tactics, UAVs may also have a propensity to move toward preprogrammed way-points. All contacts in the simulation are initially considered to be unidentified surface vessels. The scenario starts and UAVs move into the operational area toward these unknown contacts or waypoints.

Once a contact is within the UAV's classification radius, it is classified as either an enemy or a neutral. Upon classification, contact icons change to plus signs for visual reference. The UAVs have a higher propensity to move toward the enemy to gather more information. BAMS monitors enemy contacts briefly, and then "breaks lock," or moves away, to search for other contacts. VTUAVs "pounce" on enemy contacts and attempt to stay with them longer. After enemies are identified, both types of UAVs attempt to monitor them throughout the scenario. This simulates the Blue force effort to continuously update the common operational picture (COP).

This simulation is a continuous time-step model. Every time step represents 10.81 seconds of real time. The battlefield is a 1,000 by 1,000 pixel area where each pixel represents 200 by 200 meters. This set-up allows for the simulations to represent over 10,000 square nautical miles.

B. CREATIVE MODELING

This study uses two creative modeling techniques to build the model described above. Each of these techniques allows the model to overcome a specific limitation. The first technique includes the use of MANA's refueling mechanism, "stealth mode," and communication links. This technique facilitates UAV movement, collection of the time of first enemy classification on the COP, and collection of the amount of time contacts are positively identified. The second technique utilizes a weapon and "shadow ships." It facilitates collection of the time and location of first enemy classifications by a UAV, as well as the number of times that enemies are missed entirely. A description of each of these techniques follows.

1. Refueling, "Stealth Mode," and Communications

The model employs the refueling mechanism, "stealth mode," and communication links to facilitate UAV movement, collection of the time of first enemy classification on the COP, and collection of the amount of time contacts are positively identified. This technique is required to deal with the fact that BAMS needs to eventually "break lock," after it detects the presence of an enemy ship. BAMS must "break lock" so that it avoids becoming absorbed by a single enemy contact and searches for other potential hostiles.

To achieve "break lock," the BAMS agent refuels each contact that it sees. This refueling mechanism sends the contact into the "stealth mode" or stealth "trigger state." In MANA, "trigger states," allow agents to change their properties and movement characteristics based upon the

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environment or certain events in the scenario. "All entities start out in a default state, and remain in that state until a triggering event occurs," (Galligan, 2004). In this case, the act of a UAV refueling an identified contact triggers that contact to go into the "stealth mode."

If the contact has been identified as an enemy, then it stays in "stealth mode" for 83 time steps, or roughly 15 minutes in real time. During this time, the contact's stealth setting increases from 0% to 100% and BAMS can no longer see the contact (the contact also changes to a "plus sign" so that the user can visually keep track of it during the simulation). This time allows BAMS to move away from the contact, or "break lock." After 15 minutes, the enemy contact returns to its default state and appears as an unknown contact to the UAV. At this point, the contact must be identified again in order for the enemy's position to be updated on Blue force's COP.

If BAMS is not absorbed with the investigation of other contacts, it will return to the now unidentified enemy, reclassify it, refuel it, and send it into the "stealth mode" once again to update the COP. VTUAVs identify enemies and trigger them to enter the "stealth mode" in a similar manner. The amount of time in "stealth mode" generally equates to the time it takes for operators on the ship to identify the contact, realize that it is of critical interest, and vector the UAV back to the contact. Based upon the author's operational experience, this process typically takes at least 15 minutes and is a realistic estimate.

Neutral contacts and fishing vessels also enter the "stealth mode" when classified as neutrals by either type of UAV. However, the duration of time that these contacts spend in this trigger state is longer (30 minutes for neutrals and 120 minutes for fishing vessels) because they are not as critical as enemy contacts. Again, based upon the author's experience, this time is a reasonable estimate of the amount of time that might pass in between requests to visit (and revisit) these contacts in the operational area.

If VTUAVs are available, BAMS can communicate the position of enemy and neutral contacts to these VTUAVs in order to reduce its own workload. This communication reduces the chance of BAMS being absorbed by other contacts and reduces the possibility of an enemy contact eluding Blue force surveillance after initial detection.

The use of communication links also allows for the persistence of contacts on these links to determine the amount of time they are recognized by either BAMS or a VTUAV. This is a key simulation feature. If the contact persistence (the amount of time that a contact remains visible) on an agent's inorganic situational awareness (SA) map is longer than the amount of time that the contact is in "stealth mode," then that contact will never disappear from the agent's situational awareness picture.

This causes the UAV to move toward that contact and remain near it if it has the propensity to do so, a desirable property in the case of VTUAVs acting as pouncers. However, in the case of BAMS, it is undesirable. In this case, it is necessary to set the contact persistence to a much lower value than the contact's time

in "stealth mode." This gives BAMS time to orbit the contact briefly, but time also for the "stealth mode" to take effect and for BAMS to move on to another contact.

BAMS and VTUAVs each communicate the location of CCOIs and COIs to a central location (e.g., the littoral combat ship (LCS)). In this manner, the LCS acts as a communications hub for the entire force and maintains the COP. This modeling feature is not only realistic, it facilitates collection of the time of first enemy classification since this information can be directly extracted from the MANA "Record First Enemy Detections" output for the LCS squad.

While contacts are in "stealth mode," they are also given a fuel burn rate to calculate the amount of time positively identified. This burn rate is set to one unit per time step. Therefore, at the end of the scenario, the amount of fuel burned by each enemy and neutral surface contact represents the amount of time that each of these contacts is in "stealth mode." Since the "stealth mode" is triggered by the presence of a Blue force UAV, this time also represents the time that each contact has been positively classified (and remotely observed) as either a neutral or an enemy by the Blue force. The fuel state information at the end of the scenario is extracted by using the "Record Agent End State Data" feature in MANA. Therefore, the refueling mechanism, "stealth mode," and communication links are essential to proper UAV movement, collection of the time of first enemy classification on the COP, and collection of the amount of time positively identified in the simulation.

2. Weapon and "Shadow Ships"

The model employs a weapon and "shadow ships" in order to facilitate more data collection on the time and location of the first enemy classifications by a UAV, as well as the number of times that enemies are missed entirely. At the start of the simulation, each enemy ship actually exists as a squad of two ships. The first time these ships are detected by a UAV, the UAV fires one round of its "kinetic energy" weapon at the enemy squad. This results in exactly one enemy casualty. The location and time of this casualty represents the time and location of enemy classification by a UAV and are extracted by using the "Record Casualty Location Data" feature in MANA.

As a result of this casualty, one of the enemy ships dies, and the other enemy ship, the "shadow ship," continues on in the simulation. The "shadow ship" lives due to another "trigger state." In this case, when one of the enemy ships dies, the "shadow ship" enters its "squad injured trigger state" and its stealth setting increases to 100%. This prevents the "shadow ship's" detection and is similar to the "stealth mode" described earlier.

The ship stays in "stealth mode" for 83 time steps (15 minutes) until it reverts back to another "spare trigger state," which sets its stealth setting back to 0% and increases its survivability (makes it invulnerable) against the UAV weapon. Thus, the use of the UAV weapon and "shadow ship" allow for collection of the time and location of first enemy classification by a UAV. The number of misses may be calculated if the number of

casualties for each scenario is subtracted from the number of enemies present.

The time of enemy casualty identifies when the enemy ship is first seen by any UAV. However, this does not represent the first time that an enemy ship shows up on the COP of the LCS mentioned earlier. The time of first enemy classification for the LCS (on the COP) is a better representation of the time in which the Blue force first perceives the presence of potentially hostile contacts.

C.   MANA AND SCENARIO DETAILS

1.   Battlefield

For this study, the MANA "Battlefield" comes from the two maritime scenarios depicted in Chapter Two. A snapshot of the geographical map pertaining to each scenario is saved and imported in MANA as a bitmap image. In this case, the image comes from aerial maps provided by Yahoo.com. These maps are imported into MANA as terrain files. In MANA, these terrain files are then modified so that certain terrain features are recognized by agents in MANA. These terrain features include land, territorial waters, and extended territorial waters. By modifying the bitmap with the scenario map editor, the agents' ability to enter certain regions of the map can be controlled and fictional areas may be added. For this study, the territorial waters act as barriers for the UAVs and the land acts as a barrier for all surface ships.

In order to maximize the resolution of this simulation, the number of cells is set to 1,000 for both the X and Y axes. Since the area considered is a 200 kilometers by 200 kilometers square, this means there

are five cells per kilometer, or each cell is 200 by 200 meters. The battlefield settings are shown in Figure 5. These settings are found on MANA's "Setup" menu on the "Edit Battlefield" screen.

Figure 5: MANA Battlefield Settings (best viewed in color)

The Contact Aggregation Radius is reduced to a value of 1.0. This change makes it possible to separate an enemy ship from its shadow more effectively. If this number is not reduced to 1.0, it is sometimes possible for

an enemy ship's shadow to go undetected after the corresponding enemy ship is killed.

All other selections in the "Edit Battlefield" menu are at their default values.

2. BAMS

The BAMS squad represents the BAMS UAV. This squad consists of a single agent whose characteristics are based upon the operational concept RQ-4A Global Hawk Maritime Demonstration (GHMD) Brief Draft to Commander Fleet Forces Command (CFFC), (NAVAIR 5.1.1, 10 June 2004). The agent's moving propensities are shown in Figure 6. The MANA user's guide details how the movement algorithm uses these propensities (Galligan, 2004).

Propensities are adjusted with the appropriate slide bar and may take on values from -100 to 100. A higher value indicates a stronger propensity to move toward the associated agent or object. A negative value indicates a propensity to move away from the associated agent or object. Any propensity that has been changed from its default setting (0) is shown in red.

Figure 6: BAMS Propensities (best viewed in color)

The BAMS agent personality is primarily associated with the agent's inorganic SA map. The agent maintains a strong propensity to unknown contacts at 20 (on both the inorganic and squad situational awareness maps) with a stronger desire (40) to move towards Enemy Threat 3 (the enemy ships) once they are identified. The agent also maintains a –20 propensity from other friends on the inorganic SA map in order to stay away from the other VTUAVs. This setting discourages coverage by more than one

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asset in the same area. However, to ensure that this propensity does not prevent BAMS from moving toward a contact that is relatively close to a friend, but still outside of that friend's sensor range, this negative propensity is given a maximum range value of 140 (or 28 kilometers).

A very small propensity to the next waypoint (1) is provided in order to meet the positive weighting requirement for the "path following algorithm," discussed later on. (Note that this propensity changes to 30 when the Barrier tactic is introduced in Chapter Four)

The BAMS ranges are shown in Figure 7.
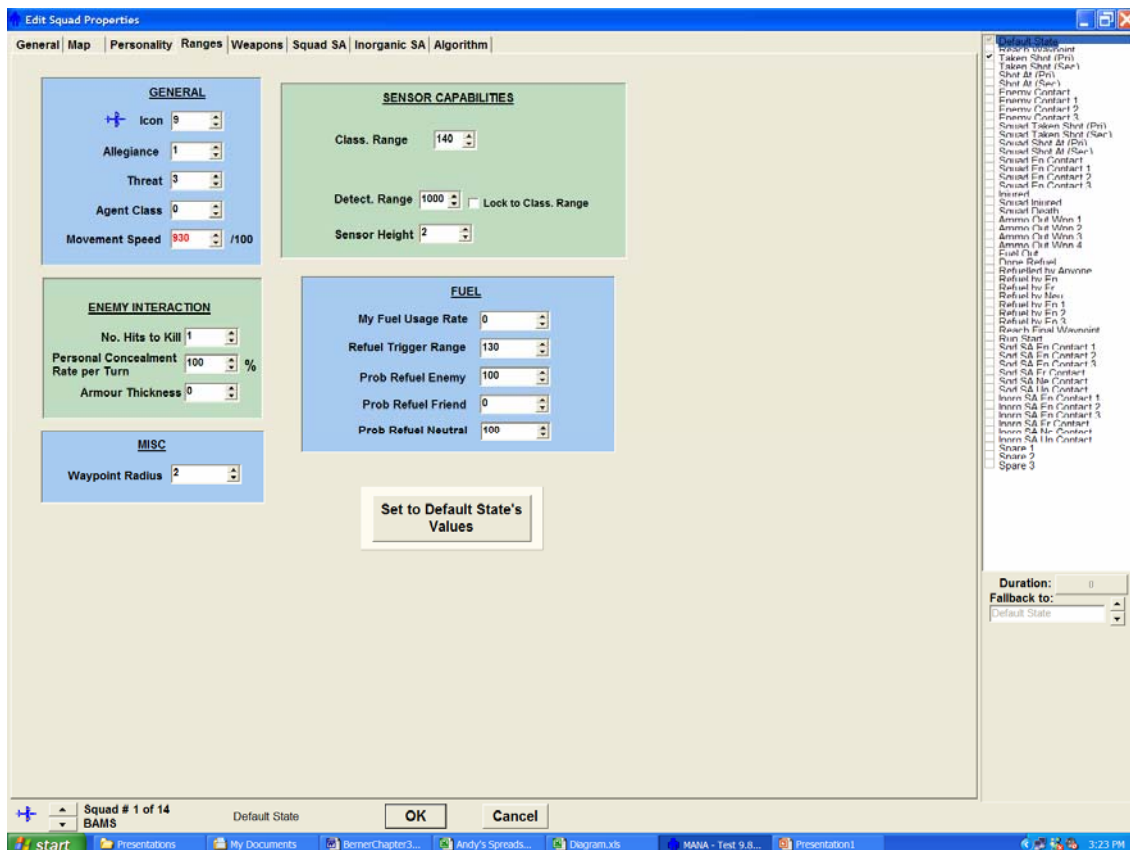
Figure 7: BAMS Ranges (best viewed in color)

BAMS allegiance is with the friendly Blue force and its speed is set to 930 in order to simulate the 335-kt air speed of the GHMD UAV. To simulate the broad area search capability of the BAMS UAV, this agent has a detection range of 1,000 (equivalent to 200 kilometers). The classification range of 140 (equivalent to 28 kilometers) represents the much shorter electro-optical/infrared (EO/IR) sensor range on board the BAMS UAV.

These settings may overstate current GHMD capabilities in that ranges are the same in all directions. Currently, GHMD radar and EO/IR sensors are limited to specific "fields of regard" from each wing tip (NAVAIR 5.1.1, 2004). It is assumed that with the overall movement of the agent, the effects of limited fields of regard would not be significant.

The personal concealment rate per turn (stealth) is set to 100% so that the flight of BAMS does not influence other VTUAV agents in the scenario. This is a realistic setting since BAMS ordinarily flies at an altitude of 65,000 feet, well above the detection range of any other player in the scenario.

As mentioned earlier, to trigger a state change in any contact that the BAMS UAV encounters, the BAMS UAV refuels contacts after they are positively identified. To enable this feature, the probabilities of refueling both an enemy agent and a neutral agent are set to 100%. The refuel range is set to 130 cells (or 26 kilometers). Note that this distance is slightly shorter than the classification range of 140 cells (28 kilometers). This difference ensures that the agent actually "sees" an unidentified contact before it is refueled. Since the act of refueling

triggers an enemy or neutral agent to go into "stealth mode," this disparity is a safeguard against an identified agent going into "stealth mode" before it is classified by the BAMS agent. The weapons configuration for BAMS is shown in Figure 8.
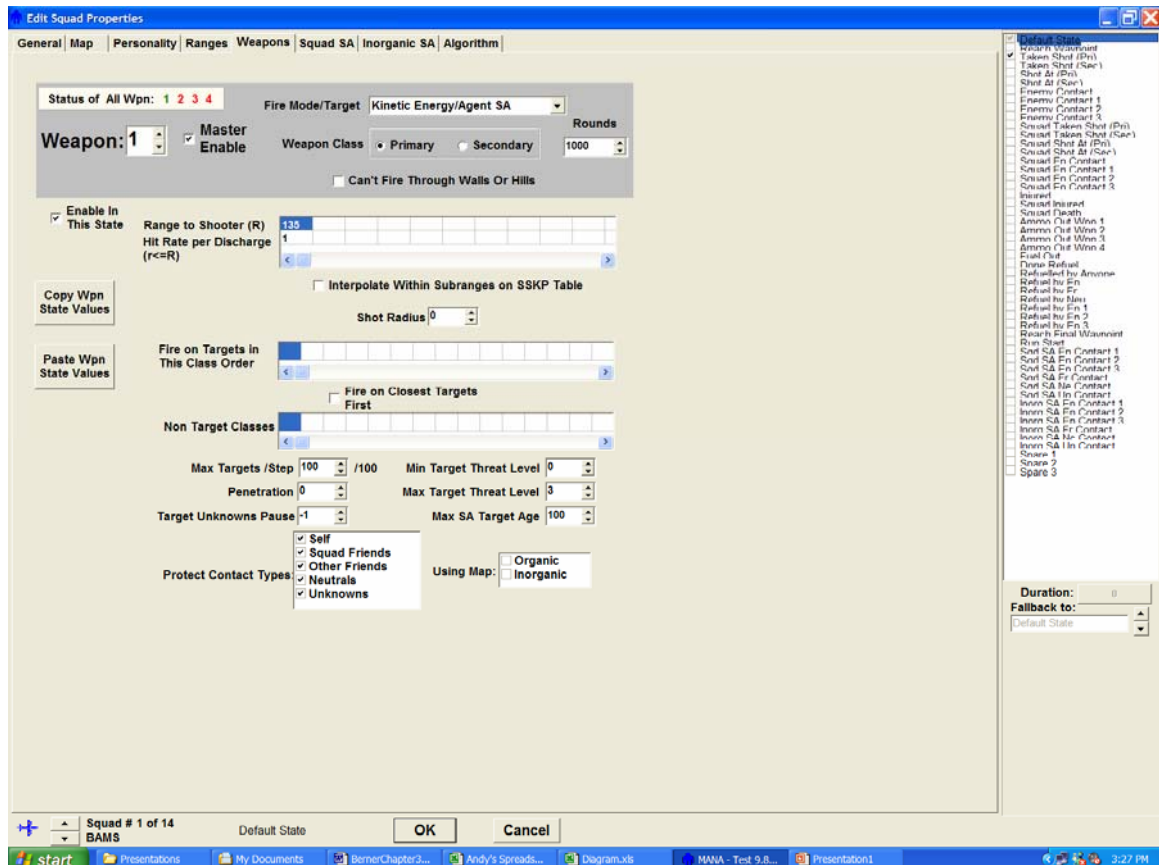
Figure 8: BAMS Weapons Configuration (best viewed in color)

The BAMS agent is modeled with a single "Kinetic Energy/Agent SA" weapon. In the Default state, the BAMS agent is provided with 1,000 rounds and is allowed to shoot at any enemy target in a 135-cell (27 kilometers) range. This range is slightly shorter than the classification range mentioned earlier to allow for some delay between contact classification and triggering of the "stealth mode." If such a delay is not incorporated,

problems sometimes occur when contacts are shot and/or go into "stealth mode" before they are registered on the inorganic SA map.

To prevent the BAMS agent from firing at other contacts, every box in the "Protect Contact Types" window is selected. The "Taken Shot" state transition also provides another safeguard. Upon classification of an enemy target, BAMS will fire its shot and kill one of the enemy ships. Then it transitions to a "Taken Shot" state in which its weapon is inactive for three time steps. This duration is just long enough for the other enemy ship to transition to the "stealth mode" before BAMS transitions back into its default state with an enabled weapon. BAMS inorganic communications are shown in Figure 9.

Figure 9: BAMS Communications (best viewed in color)

In this model, BAMS sends information about unknowns and enemies from both of its SA maps to the LCS so it can vector VTUAVs appropriately (indicated by the "UETC" setting on the communications link to squad 5).

The BAMS UAV also sends information on enemies and friends on its SA map back to itself (indicated by the "FETC" setting on communications link to squad 1). The

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information is sent back to itself in order to populate the agent's inorganic SA map. This is a necessary requirement to overcome a limitation that Galligan points out in the MANA user manual. . .

> Messages are tagged each time they are read by a squad and then passed to another. The message carries with it a list of squads that have already read it. If it ends up being resent throughout the network to one of these squads it will not allow itself to be added to that squad's inorganic picture, or to be present to any other squads. This feature is designed to prevent messages from traveling in never-ending circles in a highly interconnected scenario. (Galligan, 2004)

Because it is desired that BAMS moves based upon information from other sources, in addition to information that it obtains on its own, all information must be fused on the agent's inorganic map. This information is also passed to the LCS, where it is distributed to available VTUAVs. The LCS serves as the communications hub for all distributed sensors.

Of special importance on the communications settings are the range, capacity, queue buffer size, and delivery settings. The range of 1,500 is long enough that BAMS may be in any part of the operational space and still transmit its message to the LCS. The capacity level is set at 100% to ensure maximum "bandwidth" (i.e., to ensure that no information is lost with each transmission). The queue buffer size is set to 4 in order to prevent the model from slowing down. When information is passed to an agent, it is placed in a queue until it can be processed by that

agent. The queue buffer size refers to the maximum amount of information that can exist in this queue.

If the queue buffer size is left at the default (-1), then an infinite number of messages are allowed to be held for processing by the communicating agents. At the very beginning of the model this is not a problem, but as the simulation continues, the amount of information in the queue that the computer needs to remember increases dramatically. This overwhelms the system and slows it down drastically, to the point where instead of 2 to 4 minutes, a single run can take well over a half hour! On the other hand, if the queue buffer is set to 0, information tends to flicker on and off of the SA maps as information is stored only momentarily. Through experimentation, 4 was determined to be the fastest and most realistic setting based upon subject matter expert observation.

To speed up the model and cut down the amount of information being passed by BAMS, the "Fire and Forget" or "F-N-F" delivery mode is also selected for all BAMS communications links. The other delivery mode option is called "Guaranteed Delivery." If this option is selected, then messages will wait in the message receiver's queue until they can be read. Since BAMS constantly updates the position of all contacts that it sees, this option is not required and the "F-N-F" mode is selected to reduce queue sizes.

All other communications settings remain at their default settings, meaning that messages are sent without any latency, and with 100% reliability. The "Fuse Unknowns on Inorganic Map" box is checked so that unknown contacts may be handled more efficiently. If this box were not

checked, then the model runs the risk of being overwhelmed with an inordinate number of contacts on the inorganic SA map. Through experimentation, a Fuse Time setting of 50 and Fuse Radius setting of 10 proved to simplify the model, and still provided enough resolution to allow for proper UAV movement toward multiple unknown and classified contacts. The movement algorithms setting for BAMS are shown in Figure 10.
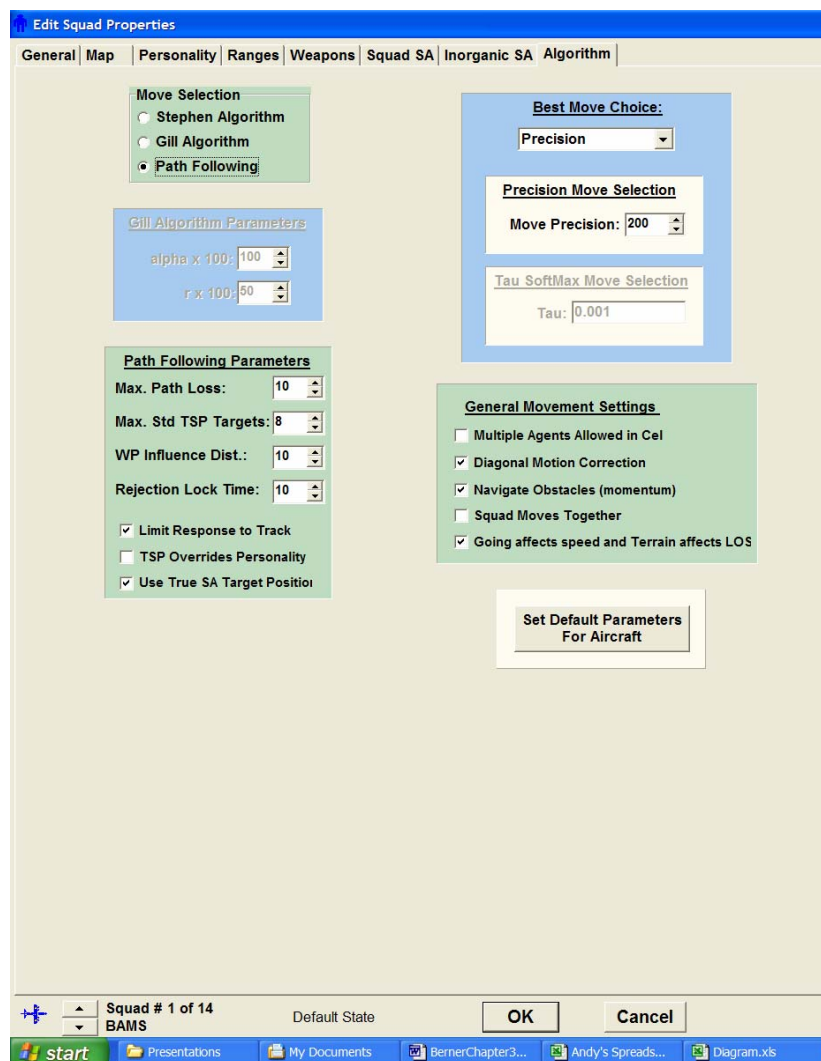
Figure 10: BAMS Movement Algorithm Settings (best viewed in color)

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This simulation takes advantage of MANA's built-in Path Following Algorithm. This algorithm "includes specialist algorithms for shortest path to visit all contacts (traveling salesman problem (TSP)) and for maintaining surveillance cover in a track—it is designed to increase the realism of aerial patrol modeling," (Galligan, 2004). This "traveling salesman problem" algorithm takes into account the nearest eight contacts, and computes the fastest way to visit all of them. The "TSP overrides personality" box is unchecked so that the personalities described earlier are taken into account. This setting allows the agent's personalities to override the TSP solution input if there is a tie in the agent's propensity to move toward a certain space in the operational area. Later in the study, when the Barrier Blue force tactic is implemented (see Chapter 4), the Stephen Algorithm is employed instead of the Path Following Algorithm to allow BAMS to move more directly through a set of Barrier waypoints. The "Going affects speed and Terrain affects LOS (Line of Sight)" box is checked to ensure that BAMS recognizes the terrain as defined in the scenario map editor and remains in international airspace.

3. Enemy Ships

As mentioned earlier, each enemy ship squad actually consists of two agents: an enemy ship and its "shadow ship." The "shadow ship" dies after the squad is initially classified by any UAV. These squads are placed at different areas in the operational area and only have a propensity of 25 to move toward their next waypoint. All other propensities are set to their default values of 0.

These squads have their allegiance set as enemies (setting 2) and a threat level of 3 so that the UAVs can recognize them as the most critical type of contacts. The squads have a movement speed setting of 41, which equates to 15 knots. This speed is not only characteristic of the cruising speed of small patrol craft, it also equates to the speed of merchant shipping in the area. By blending in with the surrounding traffic, enemy contacts are more difficult for the UAVs to pick out.

As previously discussed, the personal concealment rate per turn (stealth) of the agents in these squads varies from 0% to 100%, depending upon whether they are currently under UAV surveillance or not. Upon classification, these agents stay in stealth mode for 83 time steps, or roughly 15 minutes. This squad has no weapons or communication features.

4. Neutral Ships

There are two neutral ship squads for this simulation in order to simulate shipping traffic moving in multiple directions and in multiple shipping lanes. Each squad consists of ten agents with no allegiance to the Red or Blue force. The agents in each squad start in random positions throughout two large, rectangular boxes based upon geographical elements in each scenario. These agents move back and forth along their waypoints in a continuous loop.

Neutral ships have a propensity setting of 25 to move toward their next waypoint and a speed setting of 15 knots, or 41 cells per 100 time steps. UAVs also make these agents go into the "stealth mode" upon classification. As with the enemy ship agents, the "stealth mode" alters the

personal concealment and fuel burn rates to monitor the time that neutrals are positively identified. The only difference is that these contacts stay in the "stealth mode" for 167 time steps, or roughly 30 minutes. All other settings remain at their default settings.

5. Fishing Vessels

One squad of 30 fishing vessels is modeled for this study. This squad simply consists of 30 ships, randomly distributed throughout a large geographical box in each scenario. The ships have a neutral allegiance setting. They simulate fishing vessels that have a speed setting of 33, or 12 knots. They do not have propensities to move in any particular direction, so these ship agents move only slightly around their starting positions. They simulate vessels that are engaged in nothing more than fishing operations in their local areas. UAVs also make these agents enter the "stealth mode" upon classification.

As with the enemy ship agents, the "stealth mode" alters the personal concealment and fuel burn rates to monitor the time that fishing vessels are positively identified. The only difference here is that these fishing contacts stay in the "stealth mode" for 667 time steps, or roughly 120 minutes. All other settings remain at their default settings.

6. LCS

The LCS squad models the VTUAV host platforms and command ships. This squad consists of ships with Blue force allegiance. In the Embargo scenario, the ships start in the southwestern corner of the area. They have no speed and thus do not move in any particular direction. They simply serve as a communications hub. The original

model had LCS moving with certain propensity settings, but these features were later negated with a 0 speed setting to make the model less complex.

In the Straits scenario, this squad starts in the Northwest and moves with a propensity of 100 toward the next waypoint. A zigzagging set of waypoints before the strait gives any UAVs time to enter the gulf region on the opposite side of the strait ahead of the Blue force.

The squad has a detection range and classification range of 150 cells to simulate a typical surface radar with a range of roughly 16 nautical miles. The squad has a permanent concealment setting of 100% so that its presence does not affect UAV motion.

Communications are important for the LCS squad. The LCS receives contact data from both BAMS and all VTUAVs to populate its own inorganic SA map. The LCS sends this data back to itself so that it can then pass it back out to other assets. Data on both enemy contacts and unknowns gets passed to the VTUAVs since they have short detection radii.

Information about unknowns is not passed to BAMS since it already senses all contacts in the area with its own long-range surface radar. However, data on friendly contacts are shared so that BAMS does not waste time in areas that are already covered with VTUAVs. The range of communication is increased to 1,000 cells (200 kilometers), and the capacity of all links is increased to 100% to ensure all messages are passed. Contact persistence is set at 333, the standard VTUAV setting (see next section).

7. VTUAVs

Up to five squads of VTUAVs may be active in this simulation. At first, experiments were conducted to see whether it is better to run five different squads with one agent per squad or one squad with up to five agents. Although more complex, the first option proved to be a better choice because it enables the agents to move more independently and not collectively as one squad, much as is the case in real world operations. Each VTUAV squad is the same except for the obvious changes in destination of communications links based upon which VTUAV is referenced.

Each VTUAV squad consists of one agent with Blue force allegiance. The squad personalities are shown in Figure 11. Again, any propensities that are not left at their default settings (0) are shown in red.
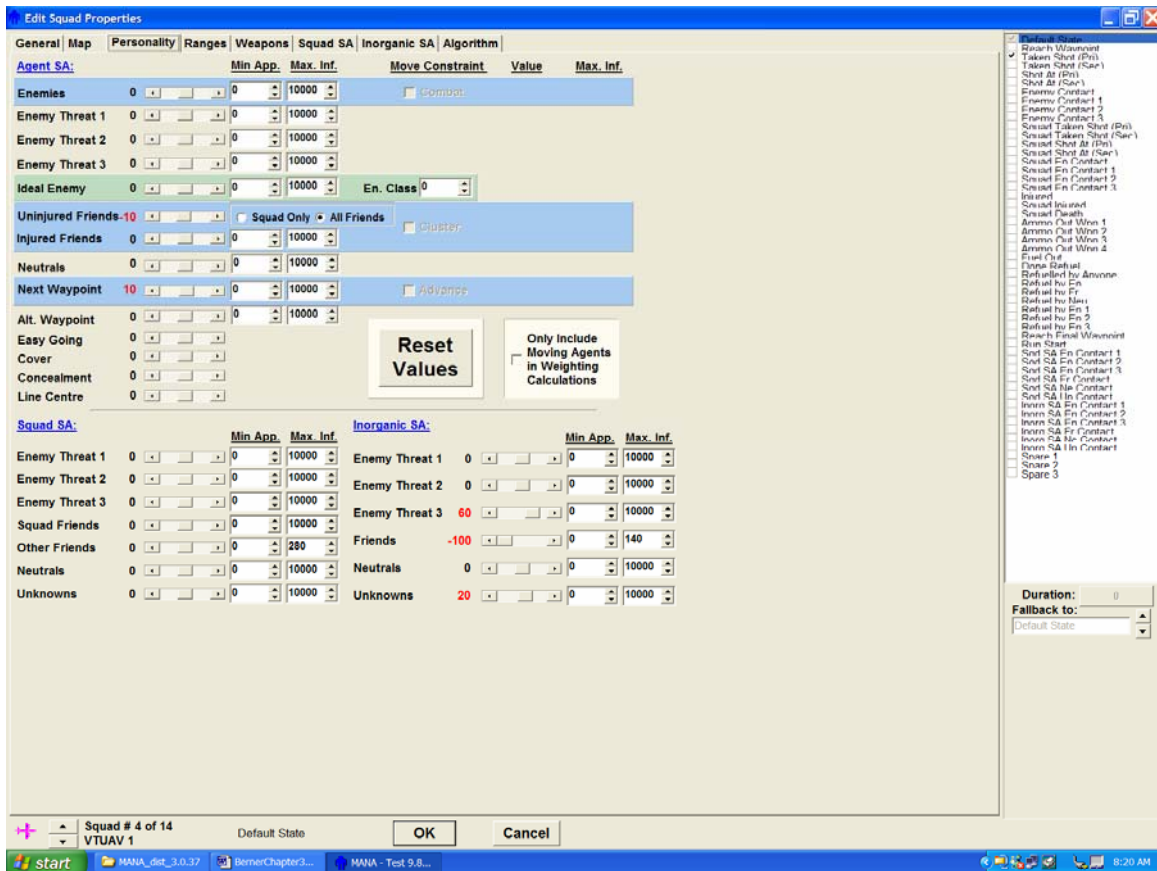
Figure 11: VTUAV Personalities (best viewed in color)

The VTUAV is similar to the BAMS UAV in that it starts off with a propensity to move to unknowns (20). However, it has a stronger propensity to move toward enemy agents (60) since it is a pouncing agent. To keep VTUAVs from clustering, these squads have a strong propensity to move away from friends (other VTUAVs) on its inorganic SA map (-100). This propensity is strong, but is limited to a maximum range of 140 cells (28 kilometers) to prevent the VTUAVs from flying off to opposite sides of the screen. These squads also have a slight propensity (-10) to move away from all uninjured friends to keep them from covering the same areas. A propensity of 10 toward their next waypoint allows the VTUAV to keep moving in the absence of

any unknown contacts when the VTUAVs operate by themselves without BAMS support. In general, these waypoints are set up simply to get the UAV into the center of the operational area. The VTUAV ranges are shown in Figure 12.
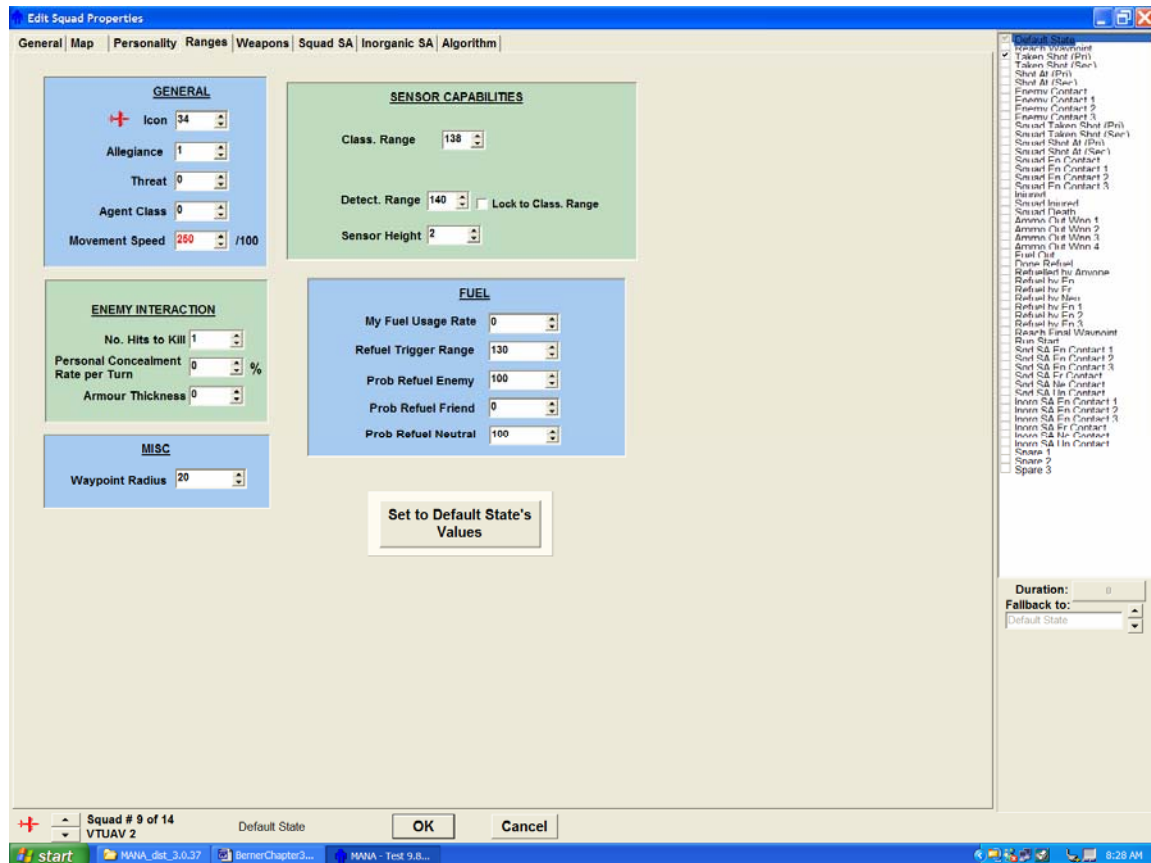
Figure 12: VTUAV Ranges (best viewed in color)

The VTUAVs move at a speed of 250 cells per 100 time steps (90 knots). This is approximately equivalent to the average cruising speed of a typical helicopter and is below the maximum speed of the Fire Scout (100 knots) (Klingbeil, 2004). These UAV agents have a detection radius of 140 cells or 28 kilometers and a slightly shorter classification range at 138 cells, or 27.6 kilometers. Although these ranges may be optimistic,

they are realistic based upon the information provided in Chapter 2.

VTUAVs have the same settings as BAMS with regard to refueling enemy contacts to make them go into the "stealth mode" when classified. They also have the same kinetic energy weapon, and state transition, to properly record the time and location of the first enemy classification. The inorganic communications page for the VTUAVs is shown in Figure 13.
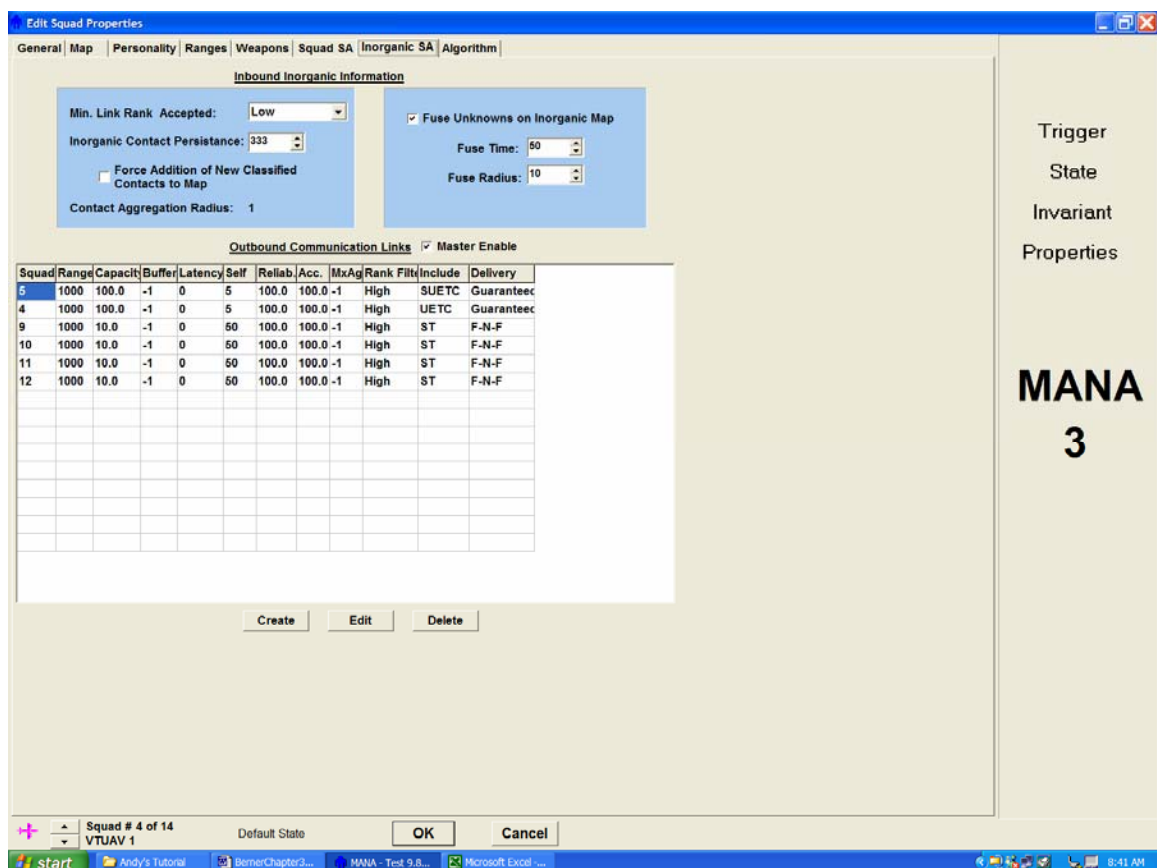
Figure 13: VTUAV Communications (best viewed in color)

The VTUAV sends all of its contact information (from both its squad situational and inorganic SA maps) to the LCS to update it with new contacts for further dissemination. The VTUAV also sends all of this

information to itself so that it may be passed properly to other agents (as did the BAMS UAV discussed earlier). Finally, each VTUAV sends its own position to every other VTUAV in order to prevent the clustering of VTUAVs. This information comes from the squad SA map and is only updated every 50 time steps (9 minutes), a setting which prevents "long tails" from forming on friendly VTUAV contact positions on other VTUAV inorganic situational maps. A "long tail" refers to the historical record of a VTUAV's position. This shows up as a tail behind the VTUAV when longer persistence settings are used. In the presence of these "long tails," VTUAVs are cut off from certain areas of the screen as they have a propensity to move away from friendly contact positions on the inorganic SA map.

The VTUAV communication links to LCS and itself have a capacity setting of 100 in order to prevent contact information loss. This setting is only 10 for the links to other VTUAVs since only one contact (the VTUAV position) is passed along. The links to VTUAVs are also set to "Fire and Forget" since they are not as critical as the other links which are set to "Guaranteed Delivery."

Of special importance on the VTUAV links is contact persistence. This value is set to 333 time steps (1 hour), greater than the amount of time that any classified contact may spend in the "stealth mode." With this setting, the VTUAV does not move away from a contact that it classifies before the contact comes out of "stealth mode." This enables the VTUAV to act as a birddog to stay near enemy contacts to collect more intelligence. The contact Fuse Time and Fuse Radius settings are the same as those discussed for BAMS. The VTUAVs use the same movement

algorithm (the Path Following Algorithm) as BAMS does, since they are also airborne contacts (see Figure 10).

The MANA model enables enough control over all agent activity to reasonably emulate real world behaviors. This provides a sound basis for experimentation and data analysis of UAV performance among the two scenarios, in different environmental conditions, to establish best practices for UAV employment and the composition of appropriate force packages.

D.   EXPERIMENTAL SET-UP, TACTICS, AND WEATHER

This section provides a brief summary of the experimental set-up involving combinations of unmanned aerial vehicles (UAVs), tactics and maneuvers, and simulated weather.

1.   Experimental Set-up

Three experiments are conducted, one for each scenario plus an additional experiment exploring weather effects in the Embargo scenario. Each experiment explores 11 different force packages with varying Red force maneuvers and Blue force tactics. These tactics are discussed in depth in the next sections. A separate section is devoted to the weather experiment in which BAMS' classification probability is varied. Table 5 summarizes this experimental set-up.

	Embargo Scenario	Assured Access Scenario	Weather Study (Embargo Scenario)
UAV Combinations	BAMS alone BAMS + 1 VTUAV BAMS + 2 VTUAVs BAMS + 3 VTUAV BAMS + 4 VTUAVs BAMS + 5 VTUAV 1 VTUAV alone 2 VTUAVs alone 3 VTUAVs alone 4 VTUAVs alone 5 VTUAVs alone	BAMS alone BAMS + 1 VTUAV BAMS + 2 VTUAVs BAMS + 3 VTUAV BAMS + 4 VTUAVs BAMS + 5 VTUAV 1 VTUAV alone 2 VTUAVs alone 3 VTUAVs alone 4 VTUAVs alone 5 VTUAVs alone	BAMS alone BAMS + 1 VTUAV BAMS + 2 VTUAVs BAMS + 3 VTUAV BAMS + 4 VTUAVs BAMS + 5 VTUAV
Red Maneuvers	Direct Coastal Combo	All Big All Small 1 Small 2 Small 3 Small 1 Big 2 Big 3 Big All Six	Combo
Blue Tactics	TSP Barrier	TSP Barrier	TSP Barrier
BAMS P(Classification)	1	1	Varies 0.01-0.1

Table 5: Experimental Set-up

All possible combinations of the experimental levels shown in Table 5 are explored in different excursions of the MANA simulation. Almost 20,000 runs of the simulation are performed on over 650 excursions. Thirty replicates of each excursion are performed where only the random number seed is changed. Results from these simulation runs are delivered in Excel spreadsheets which are later combined with an R Script file developed by Mr. Steve Upton (Referentia). These results are presented in Chapter Four.

2. Tactics and Maneuvers

Different Red force maneuvers and Blue force tactics are integrated into the experimental runs shown in Table 5. Red force activities simply involve changes in direction so they are referred to as Red force "maneuvers" or

"maneuver schemes." Changes in Blue force tactics are limited to BAMS movement. These tactics involve more complex changes to movement algorithms, and are referred to as Blue force "tactics."

a. Red Force Maneuvers

(1) **Embargo Scenario.** For the Embargo scenario, three Red force maneuvers are evaluated. The first, shown in Figure 5, is called "Direct," in which both Red force ships simply move directly across the open ocean from their starting positions to their destination in the Southeast. Operationally, the Red force might use this maneuver scheme to minimize the time required to reach its objective.
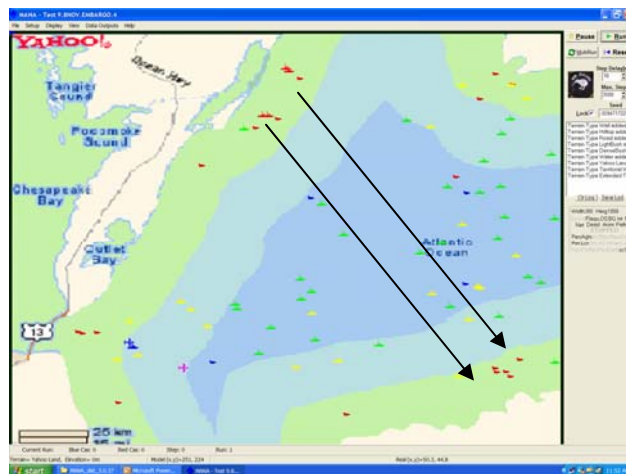
Figure 5: Red force "Direct" tactic for Embargo scenario (best viewed in color)

The second Red force maneuver is referred to as "Coastal," shown in Figure 6, in which the Red force avoids the open ocean and hugs the coast-line to arrive at the southeastern destination. Although it requires more time, this scheme might be used by the Red force in an effort to remain hidden in coastal sea clutter, exploiting the fact that Blue forces cannot enter territorial waters or airspace.
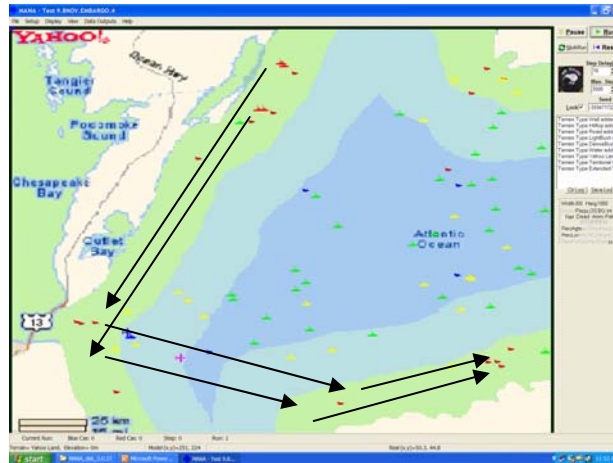
Figure 6: Red force "Coastal" tactic for Embargo scenario (best viewed in color)

The third Red maneuver scheme, shown in Figure 7, is called "Combo." Here, the Red force splits up and employs a combination of the previous two maneuvers. One ship uses the "Direct" maneuver and the other uses the "Coastal" maneuver. Operationally, the Red force might use this scheme to divide Blue force assets and improve the chances of at least one of its ships reaching the same destination without being classified by Blue. This is a more robust approach. Unlike the other maneuver schemes, in which the direction of one red unit compromises the force, the dispersed force may be more difficult to fully acquire.
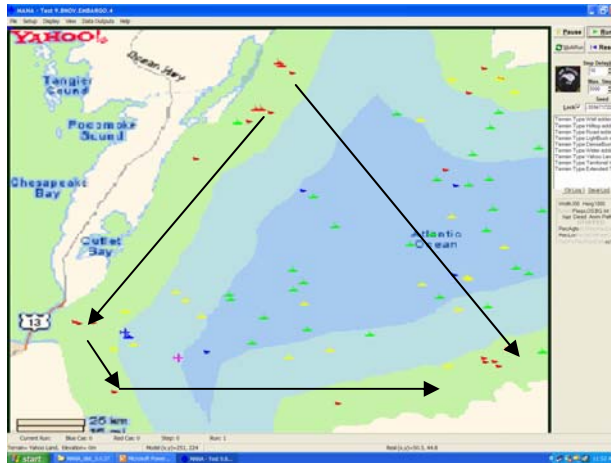
Figure 7: Red force "Combo" tactic for Embargo scenario (best viewed in color)

        (2) Assured Access Scenario. For the Assured Access scenario, nine different maneuvers are developed for the Red force. The first, "All Small," is shown in Figure 8. Here, three Red force ships travel in small patrol areas close to their initial positions. This maneuver scheme simulates a less aggressive, more defensive, Red force primarily concerned with the protection of its local area and territorial waters.
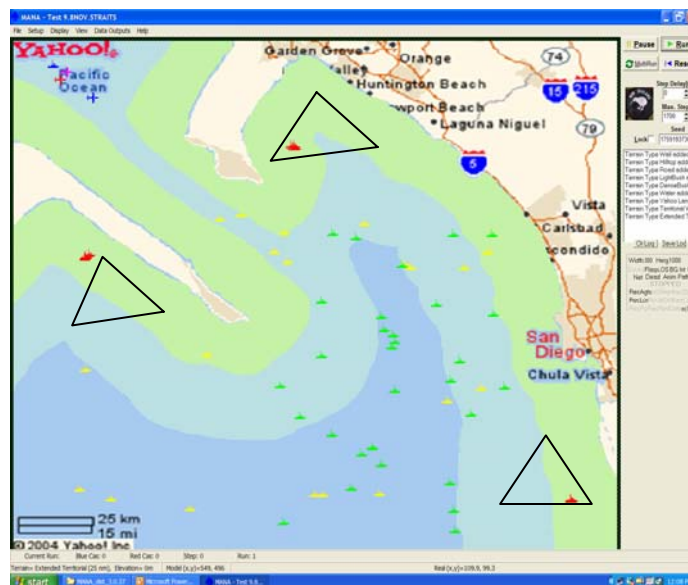
Figure 8: Red force "All Small" tactic for Assured Access scenario (best viewed in color)

The second scheme for the Assured Access scenario is called "All Big," shown in Figure 9, in which the Red forces move in larger patrol paths throughout the gulf-like region. This simulates a more adventurous Red force that actively patrols the region.
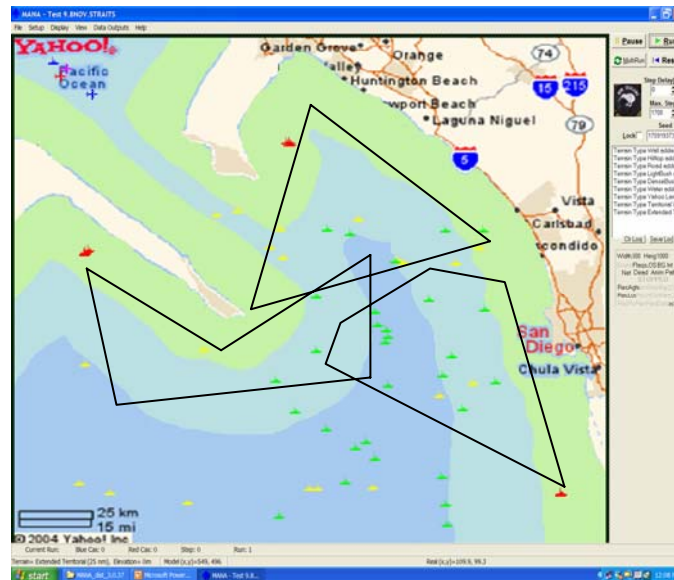
Figure 9: Red "All Big" tactic for Assured Access scenario (best viewed in color)

The ensuing five movement schemes are combinations of the "All Small" and "All Big" maneuvers representing every possible combination of the "Big" and "Small" patrol routes. One of these maneuver schemes, shown in Figure 10, employs the northernmost Red ship in a more conservative patrol within in a small area. The other two ships patrol larger routes throughout more of the operational area. These patrols represent a variety of schemes that a Red force might employ based upon varying capabilities of ships and their crews, or perhaps in an effort to hold a portion of its ships in reserve to use against any entering Blue force later on.
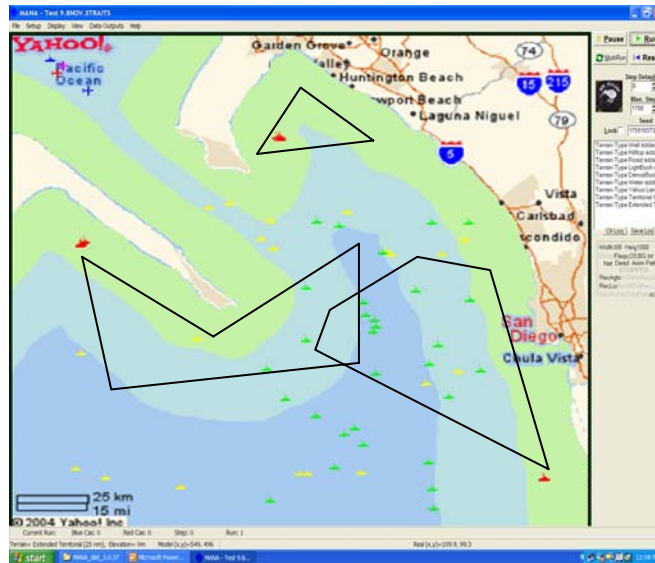
Figure 10: Red "Combo" tactic for Assured Access scenario (Best viewed in color)

The final Red maneuver scheme for the Assured Access scenario employs six squads of enemy ships. This maneuver scheme, called "All Six," is shown in Figure 11.
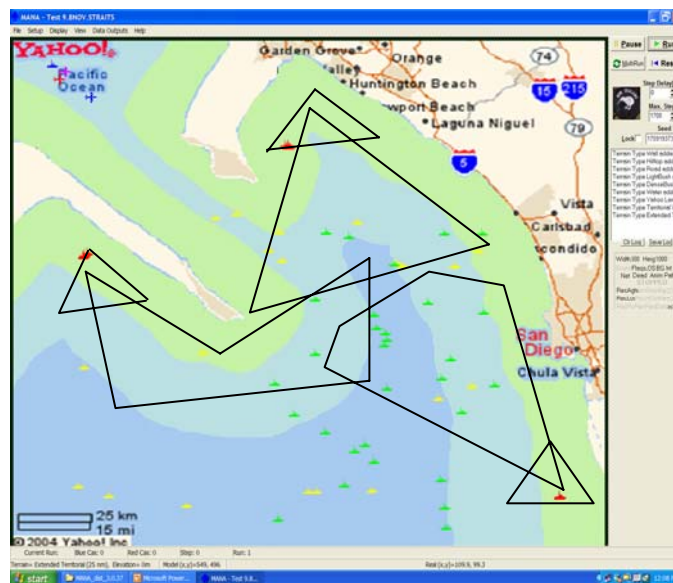
Figure 11: Red "All Six" tactic for Assured Access scenario (best viewed in color)

This tactic is a combination of the "All Small" and "All Big" maneuver schemes. Two squads start out at each Red force location. From there, one squad patrols

along a smaller area and the other exhibits a larger patrol route. This scheme represents an attempt by the Red force to maximize its coverage, or to flood the entire area with an increased operational presence.

b. *Blue Force Tactics*

Two different Blue tactics for each scenario are evaluated. These tactics consist of a "TSP" or "traveling salesman problem" tactic and a "Barrier" tactic.

(1) TSP. The "TSP" tactic simply has the Blue force Broad Area Maritime Surveillance (BAMS) UAV fly throughout the area according to the traveling salesman problem solution provided by MANA's Path Following Algorithm (as discussed in Chapter Three). This tactic is realistic. BAMS can detect all contacts in the area of interest with its maritime surveillance (MS) radar. Typically, contact detections will cause any preprogrammed routing to be regularly modified for mission as the mission progresses.

The "TSP" tactic has its advantages and disadvantages. While it allows for continuous modification and exploration of the entire area, it increases the chance that BAMS might get absorbed with contacts in one particular location permitting a missed enemy classification elsewhere. The "TSP" tactic uses the same MANA settings in both scenarios.

(2) **Barrier Tactic.** The "Barrier" tactic focuses BAMS sensors along one particular route segment. This tactic may be more reasonable for the Blue force if it knows that the Red force is trying to reach a certain location, or if it wants to clear a specific corridor.

This tactic also has its advantages and disadvantages. Given its relatively high speed and wide sweep width, it is less likely that enemy ships would be able to penetrate any "Barrier" without being classified by BAMS. The disadvantage to this tactic is that it normally requires some intelligence on where the Red force wants to go. Also, times to first enemy classification will probably be higher, as BAMS must wait for the Red force to come closer to the "Barrier" track.

To achieve the "Barrier" tactic in MANA, BAMS' propensity to move to the next waypoint is increased from 1 to 30, and the movement algorithm is changed from the Path Following Algorithm to the default heuristic (known as the Stephens Algorithm in MANA) using a specific set of waypoints. These changes force the agent to move more directly along a specific track according to the basic penalty calculation in MANA instead of the "TSP"-type of algorithm (Galligan, 2004).

For the Embargo scenario, the specific set of waypoints lies across the shipping lanes in front of the Red force destination in the southeastern portion of the operational area, as shown in Figure 12.
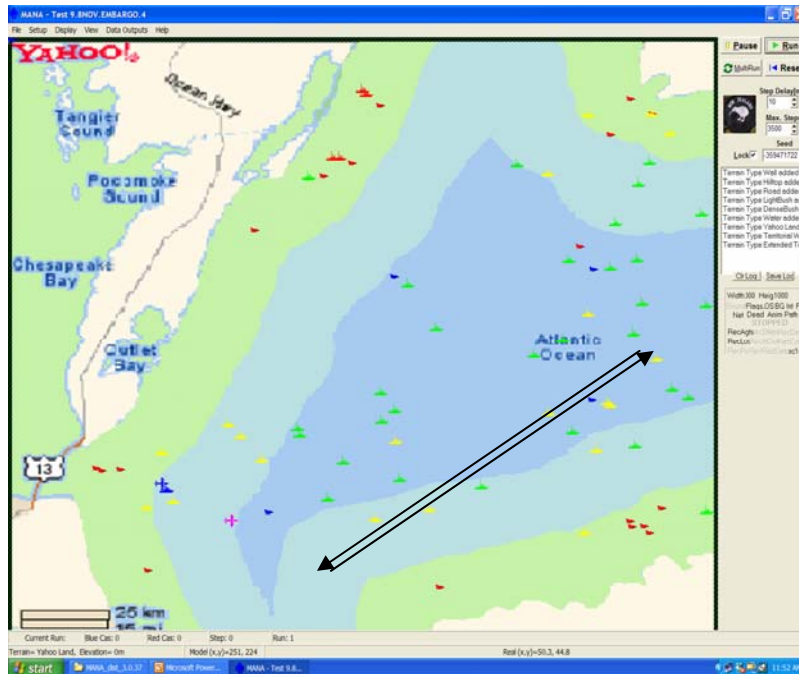
Figure 12: Blue force "Barrier" tactic for Embargo scenario (best viewed in color)

For the Assured Access scenario, the "Barrier" tactic allows the Blue force to concentrate its search in the area of immediate interest. BAMS' track is focused along the Blue force intended path to ensure safe transit. The waypoints take BAMS through the strait, and back and forth along the major shipping channel in the area of interest, as shown in Figure 13.
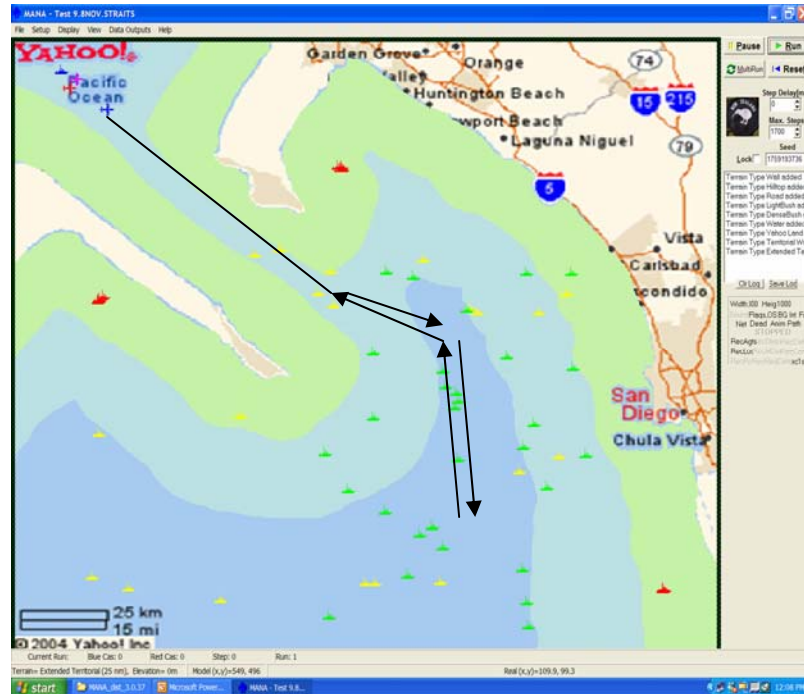
Figure 13: Blue "Barrier" tactic for Assured Access scenario (best viewed in color)

Data are collected from experiments in each scenario, among every combination of available UAVs, Red force maneuver schemes, and Blue force tactics. Results for both scenarios are provided in Chapter Four.

(3) **Accounting for Weather.** Apart from experiments that explore the effects of different UAV combinations and tactics, a separate study examines the effects of weather. This advanced study reduces the probabilities of classification for the BAMS UAV in order to simulate the effects of clouds on its ability to classify contacts. The VTUAV probabilities remain unchanged; therefore, this study models the effects clouds above the typical altitudes for VTUAVs and below the typical altitudes for BAMS (between 20,000 and 65,000 feet) (Klingbeil, 2004 and NAVAIR 5.1.1, 2004). Since clouds tend to reduce the capability of EO/IR sensors, decreases in BAMS' probability of classification are used to model

their effects (NAVAIR Weapons Division, 2003 and TM 3-22-5-SW, 2004).

The MANA Users Manual (Galligan, 2004) carefully points out that MANA actually models probabilities of classification as glimpse probabilities. The manual states. . .

> Classification rate...is per turn—not per model iteration. The cumulative probability of classification increases when an agent stays within classification range over a number of turns. For example, if an agent maintains a constant position from a sensor that has a 25% classification rate per turn then after 10 turns there is a 94% (cumulative) probability that that agent contact has been classified. (Galligan, 2004)

Similarly, a UAV's contact classification probability does not improve when that UAV stays in the same weather for long periods of time. Therefore, MANA's classification rates must be translated into cumulative probabilities to properly simulate weather effects.

To calculate the cumulative probabilities, the number of glimpses (or amount of time steps) required to calculate the cumulative probability is based upon the speed of the BAMS UAV and twice its sensor range. This range allows the contact enough time to enter and exit the UAV's classification radius, while the UAV flies directly over the contact. In this case, the number of glimpses is equal to 280 cells (twice BAMS' classification range) divided by 9.30 (BAMS speed in cells/time step).

The cumulative probability can then be calculated with the following formula:

$$\text{Cumulative Probability} = 1-(1-p)^{\wedge}(n).$$

Where n is the number of glimpses and p is the classification probability per glimpse.

Using this formula, Table 6 shows the cumulative probabilities of classification with respect to varying glimpse probabilities for the BAMS UAV.

Glimpse Probability	Cumulative Probability
0.01	0.26
0.02	0.45
0.03	0.60
0.04	0.71
0.05	0.79
0.06	0.84
0.07	0.89
0.08	0.92
0.09	0.94
0.10	0.96

Table 6: Probabilities of Classification for BAMS UAV

Note that very small increases in glimpse probabilities equate to relatively large cumulative probabilities. Hence, for this study, in MANA, the classification rates are only changed from 0.01 to 0.1 in increments of 0.01 (enabling the probabilities of classification to range from roughly one-in-four, to 95%). This study discusses the effects of these varying probabilities on the time to enemy classification and the amount of time positively identified.

Results from the MANA implementation and experimental set-up described in this chapter are presented and analyzed in Chapter Four.

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IV. EXPERIMENT ANALYSIS AND RESULTS

This chapter describes the results from this study and is divided into three sections. The first section discusses the results for the experiment with the Embargo scenario. The second section discusses results from the Assured Access scenario. The last section is devoted to analysis of an experiment on the effects of weather.

To meet expectations, unmanned aerial vehicles (UAVs) should help decision-makers by providing a picture that is on time, complete, and continuous. Therefore, the sections in this chapter speak to UAV timeliness, completeness, and classification continuity on the common operational picture (COP). In terms of time, the Blue force objective is to minimize the time it takes to classify enemy contacts despite different enemy maneuvers. The Blue force also needs to classify enemy contacts in advantageous locations, either before they get to their smuggling destinations, or before they can impede the progress of the Blue force. In terms of completeness, second enemy classification times can be important, and the Blue force needs to prevent any missed enemy classifications, or leakers. In terms of continuity, the Blue force seeks to keep all contacts classified for as long as possible, in order to maintain a more complete COP.

The ability to meet these objectives is affected by tactics and the number of UAV assets available, but the Broad Area Maritime Surveillance (BAMS) UAV should still prove to be a force multiplier. BAMS is a relatively fast asset, has a long-range maritime surveillance (MS) radar,

and can communicate the locations of all contacts in the area of interest to any available Vertical Take-Off Unmanned Aerial Vehicles (VTUAVs). Therefore, UAV combinations with BAMS are expected to out-perform combinations without BAMS.

BAMS should be able to classify the enemy sooner, in a less critical location, for longer periods of time. However, the results show that these expectations are not always met, or vary, depending upon the combination of UAVs, tactics, and maneuvers involved. The analysis explores these cases in detail.

It should be noted that for the level of resolution in this study, there is no difference between classification and identification. This is due to the level of resolution of the modeling software. Therefore, the time between detection and identification actually refers to the time when a contact is classified as either a neutral or an enemy. Similarly, the amount of time positively identified refers to the duration of time that a contact is classified as either a neutral or enemy.

A. EMBARGO SCENARIO RESULTS

1. Timeliness in Establishing the COP

The goal of the Blue force in this experiment is to classify all enemy contacts as soon as possible. Operationally, shorter times to classification enable the Blue force to react sooner to the presence of potential hostiles. With its high-speed and long-range radar, combinations with BAMS should be able to identify enemy contacts faster.

Surprisingly, the results for the Embargo scenario show that this is not always the case. A plot of the average time until the first enemy classification on the COP provides initial insights in Figure 14. These data, in particular, come from an experimental series in which the Blue force uses the "TSP" tactic and the Red force uses the "Combo" maneuver.
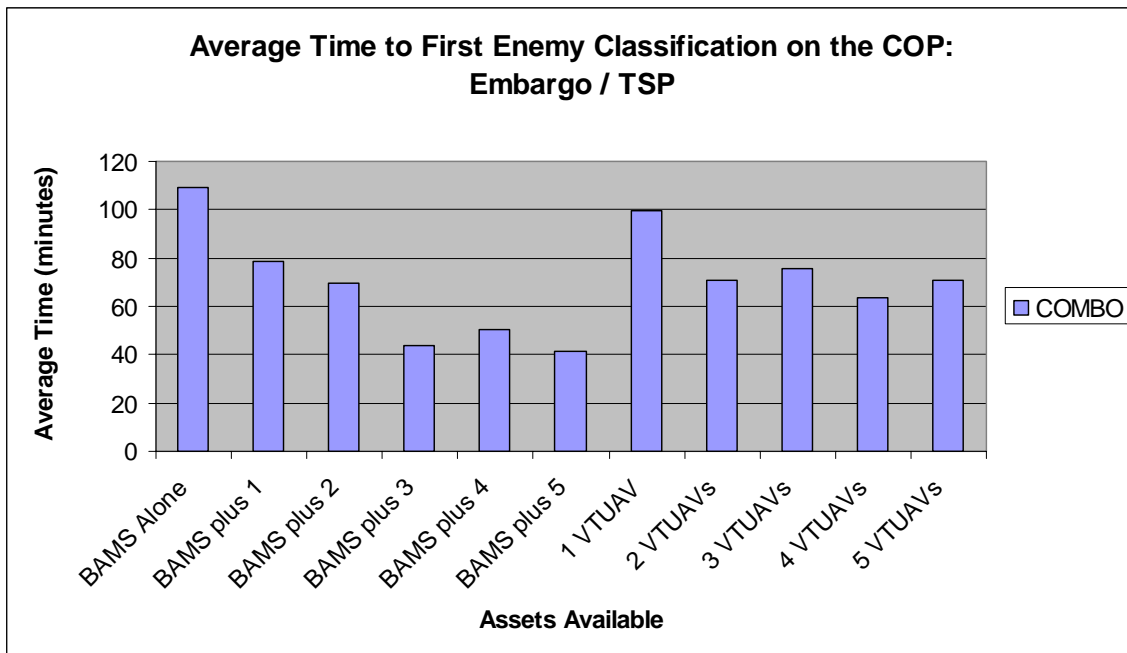
Figure 14: Average Time to First Classification on the COP for Embargo scenario with Blue force using "TSP" tactic and Red force using "Combo" maneuver (best viewed in color)

At first glance, expectations are confirmed by the fact that the quickest times to first enemy classification are yielded by the BAMS plus three VTUAV force. This force classifies the enemy roughly 18 minutes before any other combination with fewer VTUAVs. This amount of time may or may not be significant, depending upon the nature of the conflict and how much time the Blue force has to coordinate a response to intercept the Red force. Interestingly, when

BAMS is present, the addition of a fourth or fifth VTUAV does not significantly improve the results. Without BAMS, the addition of a third, fourth, or fifth VTUAV does not appear to significantly improve force effectiveness. This suggests that perhaps there is a point of diminishing returns, or a "knee in the curve," with the addition of two or three VTUAVs.

Contrary to expectations, this graph also indicates BAMS does not provide a significant advantage over the use of VTUAVs in all combinations. In fact, the time until first enemy classification is greater with BAMS alone (108 minutes) than it is with a single VTUAV (99 minutes). Upon further analysis with the model, it appears that this difference has to do with the initial vectoring of the VTUAVs. In this model, the VTUAVs' initial waypoints lead them toward the enemy faster than BAMS.

Despite this result, after three VTUAVs are available, the scenarios with BAMS make the first enemy classification sooner than when BAMS is not available. In general, the results for BAMS plus three, BAMS plus four, and BAMS plus five VTUAVs are each more than 18 minutes faster than three VTUAVs, four VTUAVs, and five VTUAVs alone. A box and whisker plot describes the data further in Figure 15.
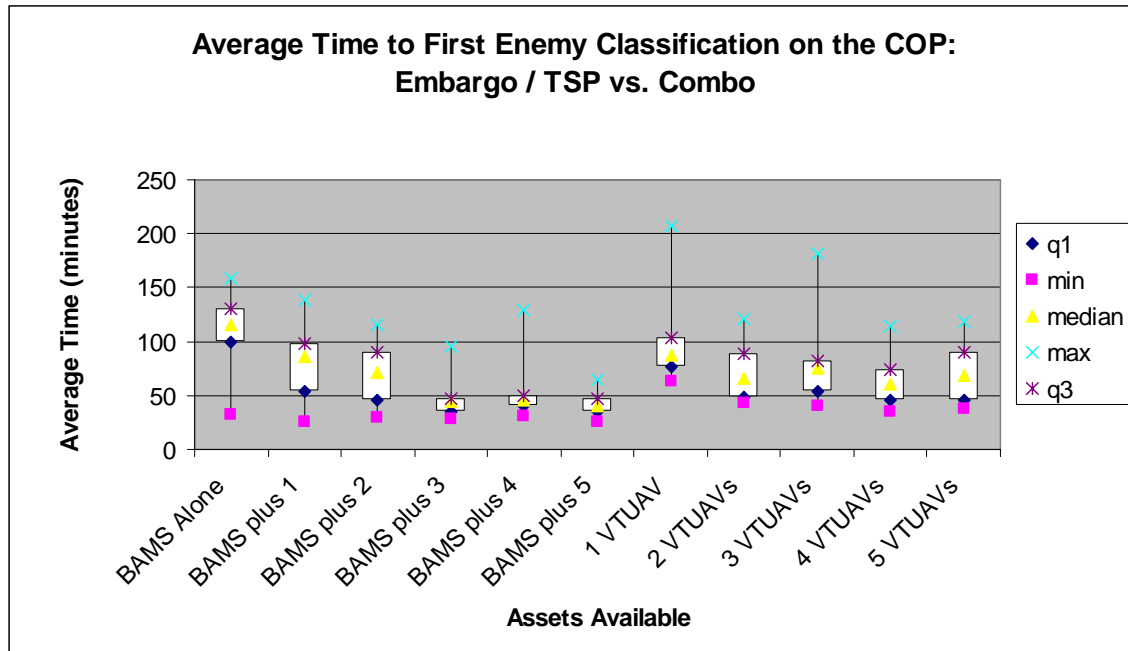
Figure 15: Box and Whisker plot of Average Time to First Enemy Classification on the COP for Embargo scenario with Blue "TSP" tactic versus Red "Combo" maneuver (best viewed in color)

This plot provides a better indication of the distribution of data by showing where the minimum, median, and maximum values lie, as well as the boxed inter-quartiles. For each distribution, 50% of the values lie within these boxes. If any two boxes contain the same values on the vertical axis, they are said to overlap. Non-overlapping boxes are a good indication of statistical differences since 50% of the values in each sample must be different. The minimum and maximum values, connected to the box via "whiskers," provide an idea of each distribution's overall spread.

Figure 15 shows the differences in variability in scenarios with BAMS and three or more VTUAVs versus all other combinations. With respect to 50% of the values (the inter-quartile box), there is less overlap, and therefore less statistical difference, between the

BAMS plus one or BAMS plus two VTUAVs cases and the two through five VTUAVs alone cases. Again, this suggests a payoff with three additional VTUAVs. The payoff is approximately equal for the BAMS plus four and BAMS plus five VTUAVs cases.

Comparing their mean first classification times confirms these results. Table 7 shows the results of a t-test performed on the data from BAMS plus one and BAMS plus two VTUAVs.

t-test: Two-Sample Assuming Unequal Variances

	BAMS + 1	BAMS + 2
Mean	78.46	69.40
Variance	899.39	752.95
Observations	30.00	30.00
Hypothesized Mean Difference	0.00	
df	58.00	
t Stat	1.22	
P(T<=t) one-tail	0.11	
t Critical one-tail	1.67	
P(T<=t) two-tail	0.23	
t Critical two-tail	2.00	

Table 7: t-test Results for BAMS plus one VTUAV versus BAMS plus two VTUAVs

In this test, the null hypothesis is that there is no difference in average performance between BAMS plus one VTUAV and BAMS plus two VTUAVs. The alternate hypothesis is that the mean times for BAMS plus one VTUAV are greater than BAMS plus two VTUAVs. The p-values, the smallest level of significance at which the null hypothesis would be rejected, for both the one-tail and two tail test (0.11 and 0.23, respectively) are greater than 0.05. Therefore, we cannot reject the null hypothesis with confidence. By convention, if the p-value is less than 0.05, then we say that the difference between means is "statistically significant" at the 0.05 level (Devore, 2000). Since this

is not the case here, we cannot conclude that BAMS plus two VTUAVs is significantly better than BAMS plus one VTUAV.

However, if BAMS plus two is compared with BAMS plus three VTUAVs, the results change. Table 8 lists the results for this t-test.

t-test: Two-Sample Assuming Unequal Variances

	BAMS + 2	BAMS + 3
Mean	69.40	43.98
Variance	752.95	167.85
Observations	30.00	30.00
Hypothesized Mean Difference	0.00	
df	41.00	
t Stat	4.59	
P(T<=t) one-tail	2.081E-05	
t Critical one-tail	1.68	
P(T<=t) two-tail	4.163E-05	
t Critical two-tail	2.02	

Table 8: t-test between BAMS plus two VTUAVs and BAMS plus three VTUAVs

The p-values for this test are very close to 0, indicating that the null hypothesis that the two means are the same can be rejected even at the 0.0001 level. Therefore, it is safe to say that BAMS plus three VTAUVS provides faster times to first enemy classification than BAMS plus two VTUAVs. There is also much less variability in the BAMS plus three combination, as its variance is much lower, at 167.85, than BAMS plus two at 752.95. Again, looking at Figure 15, one can readily see the difference in performance.

Similar t-tests show that BAMS plus three is better than any VTUAV combination without BAMS. Other t-tests also show that BAMS plus one VTUAV provides faster classification times than BAMS alone.

From this information, BAMS seems to provide an improvement in the time to first enemy detection, but only

when there are more than three VTUAVs available.   This
result is specific for the Embargo scenario, using the
Blue "TSP" tactic and Red "Combo" maneuver.   The
improvement is about 18-36 minutes.

a.   Effects of Tactics on Classification Time

The next section addresses what happens to this
result when Red or Blue tactics change.   Results when all
Red maneuvers are included are shown in Figure 16.

Figure 16: Average Time to First Enemy Classification on COP for the
Embargo scenario with Blue "TSP" tactic (best viewed in color)

On the whole, the Blue force is most effective at
first classification times when BAMS operates with at least
three VTUAVs.   In terms of maneuvers, this also suggests
that the "Coastal" maneuver is the most challenging for the
Blue force and results in the greatest times to first enemy
detection.   In contrast, the "Direct" maneuver results in
the shortest times and seems to be the least challenging
for the Blue force to work against.

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These results make sense. It should take longer for UAVs to find contacts that are closer to the coast when so many other contacts need to be classified in the center of the maritime space. Intuitively, more "Direct" Red movement should be the most straightforward since the UAVs cover this open area more often in order to identify the majority of contacts. This provides an element of force validation to the simulation model.

In cases without BAMS, two VTUAVs seem to be sufficient in providing the shortest times to classification, most likely due to the initial propensity to move away from each other and allowing for better coverage. If one VTUAV heads in the wrong direction in its initial vectoring, the other points in a better direction. These favorable conditions more or less persist when more VTUAVs are available and point to a tactical procedure for programming autonomous VTUAVs.

Changing Blue tactics to the "Barrier" patrol instead of "TSP" yields the results depicted in Figure 17.
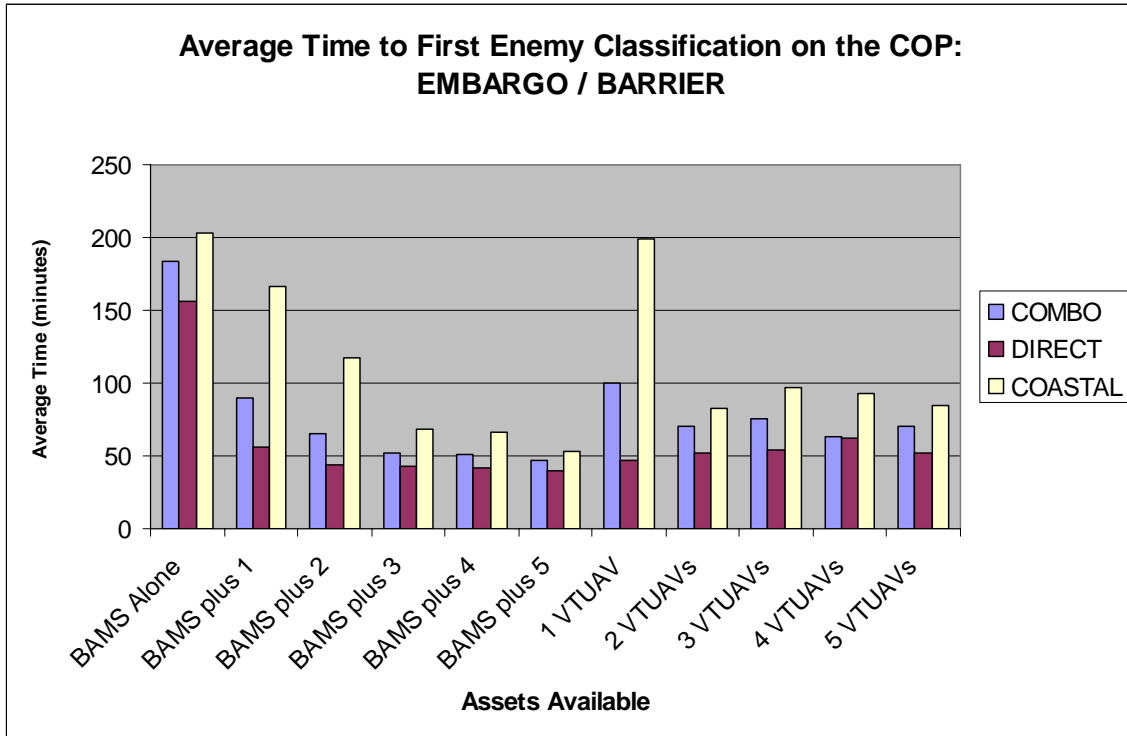
Figure 17: Average Time to First Enemy Classification on the COP for Embargo scenario with Blue "Barrier" tactic (best viewed in color)

When Blue runs the "Barrier" tactic, the results are similar to the "TSP" tactic for all Red maneuvers, except that longer times are returned when BAMS operates alone. This result makes sense. With the "Barrier" tactic, BAMS no longer actively moves into the operational area at the start of the simulation. Instead, BAMS stands off, moving back and forth along a barrier. This naturally results in longer times to first enemy classification.

Figure 17 also reinforces the result of the previous section. Across all Red activity, the best UAV combination seems to be BAMS plus three VTUAVs. This combination provides the shortest times to first enemy classification, even when the Red force runs the "Coastal" maneuver. In terms of time until the first enemy classification on the COP, regardless of any Blue or

Red force tactics, the best combination of assets is BAMS plus three VTUAVs for the Embargo scenario.

The results for the time to first enemy classification by any UAV for the Embargo scenario are only slightly different. As mentioned in Chapter Three, these results come from the time of the first and second enemy classifications based upon the casualty location data obtained in MANA.

Figure 18 shows the results for the time of first enemy classification by any UAV for the Embargo scenario when the Blue force uses the "TSP" tactic.

Average Time to First Enemy Classification by any UAV: TSP / EMBARGO
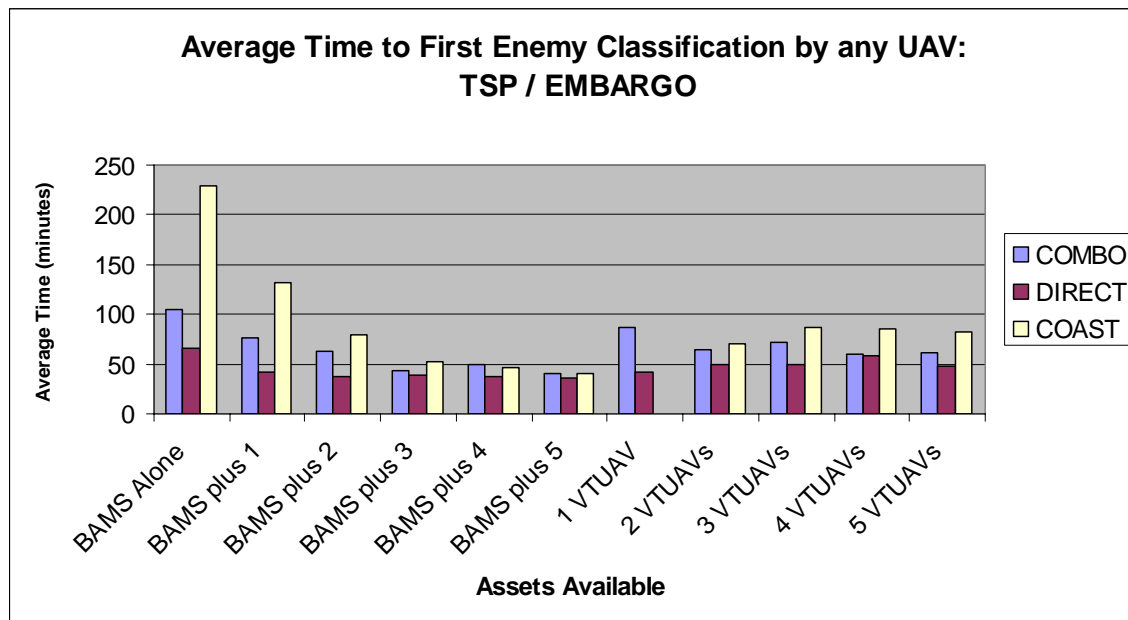
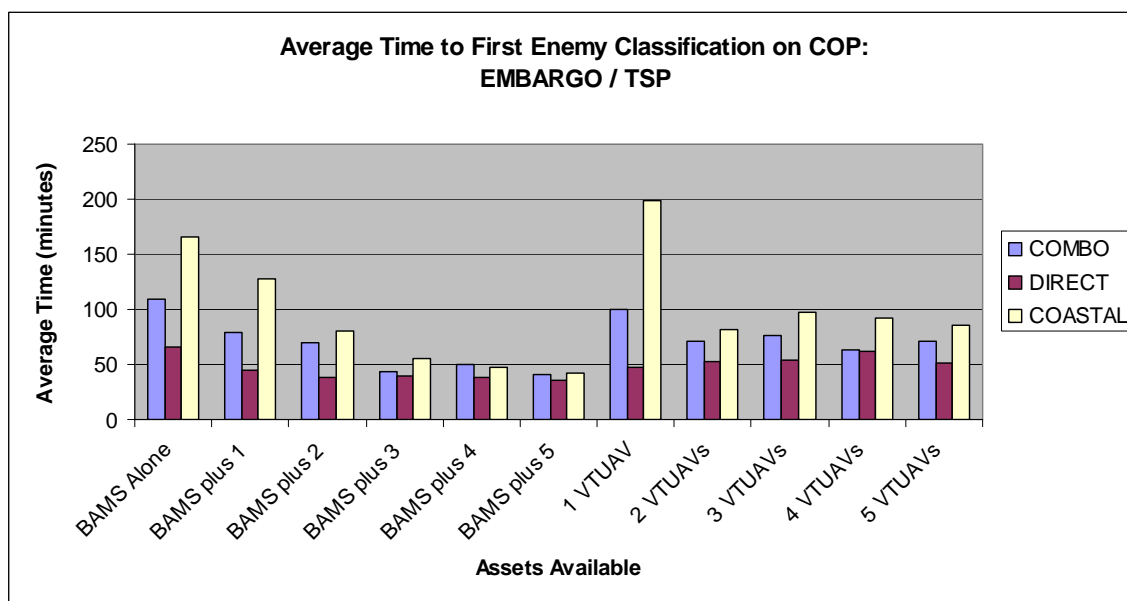**Figure 18:** Average Time to First Enemy Classification by any UAV for Embargo scenario with Blue "TSP" tactic (best viewed in color)

These results concur with the previous results about the COP; that is, BAMS plus three VTUAVs is the best combination. Again, "Coastal" maneuvers by the Red force make operations most difficult for the Blue force, for whom a single VTUAV results in no detection time at all. This

indicates that, while times to classification are a valid performance measure, missed classifications, or leakers, may be a problem. This issue is discussed further in subsection 2, "Completeness in Establishing the COP."

It should be noted that sometimes the results by any UAV (shown in Figure 18) vary from the results from the COP (shown in Figure 17). This is because the results from the COP actually represent the time that the Littoral Combat Ship (LCS), which is the fusion node for the COP, makes its first enemy classification. Since the LCS does have its own organic sensor detection and classification range, it is possible for the LCS to make its own classifications. Sometimes this fact results in an earlier classification time for the COP than for the UAVs alone (e.g., in the "Coastal" tactic with BAMS alone iteration).

Figure 19 shows the results for the First Enemy Classification by any UAV for the "Barrier" Blue force tactic.
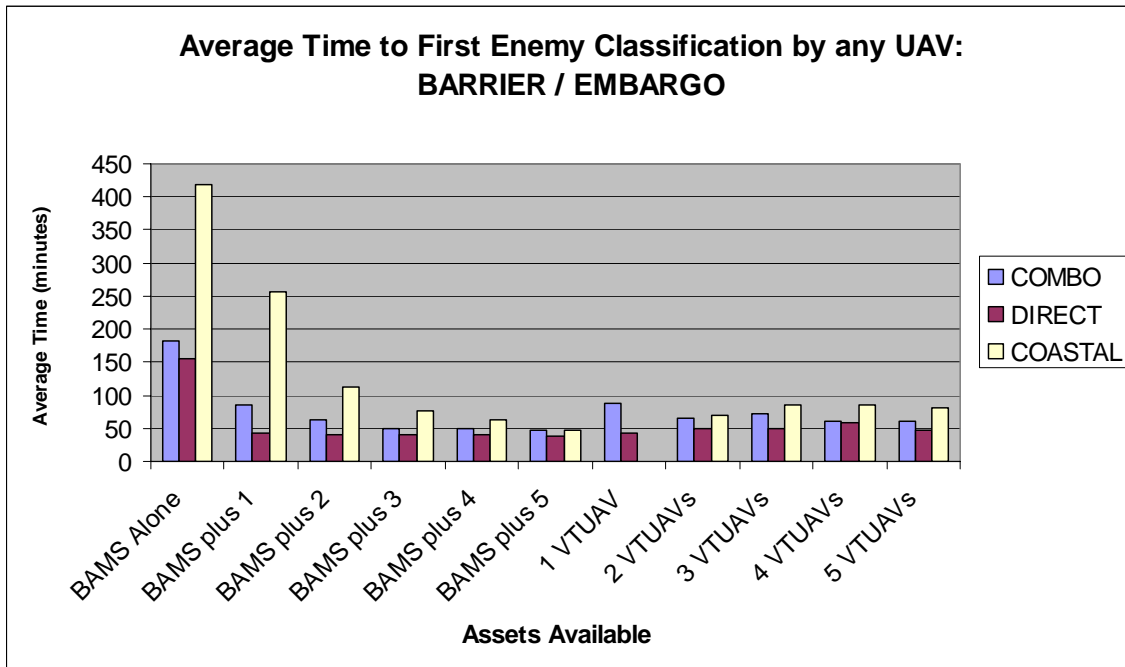
Figure 19: Average Time to First Enemy Classification by any UAV for Embargo scenario and Blue "Barrier" tactic (best viewed in color)

These results show that it takes longer to make the first enemy classification when BAMS operates with fewer VTUAVs, especially when the Red force chooses the "Coastal" tactic, since BAMS flies the "Barrier" patrol waiting for the Red force to approach the barrier. This data also shows, again, that the worst combination for the Blue force is to operate with a single VTUAV against the Red "Coastal" tactic. The lack of success against the "Coastal" target for one VTUAV indicates the shortcoming of relying on this style of platform.

b.   Classification Location as an Indicator of Timeliness

Location data from MANA can be used to plot the position of the first and second enemy classifications. Classification locations are an important indication of what types of tactics give the Blue force the most time, or space, to react. Figure 20 shows these average locations

for the Embargo scenario when the "TSP" tactic is used against all combinations of UAVs and Red tactics.

Figure 20: Average Locations of Enemy Classifications by any UAV for Embargo scenario with Blue "TSP" tactic (best viewed in color)

This figure shows that for most combinations with the "TSP" tactic, classifications are made in the northwest portion of the area. The outlying classifications, occurring more toward the South, are the second classifications by the BAMS alone or single VTUAV combination versus the Red "Combo" maneuver. These second classifications occur late in the scenario and verify that the "Combo" maneuver is most effective in distracting the attention of small numbers of UAVs.

Figure 21 shows the average locations of classification when the "Barrier" tactic is used.
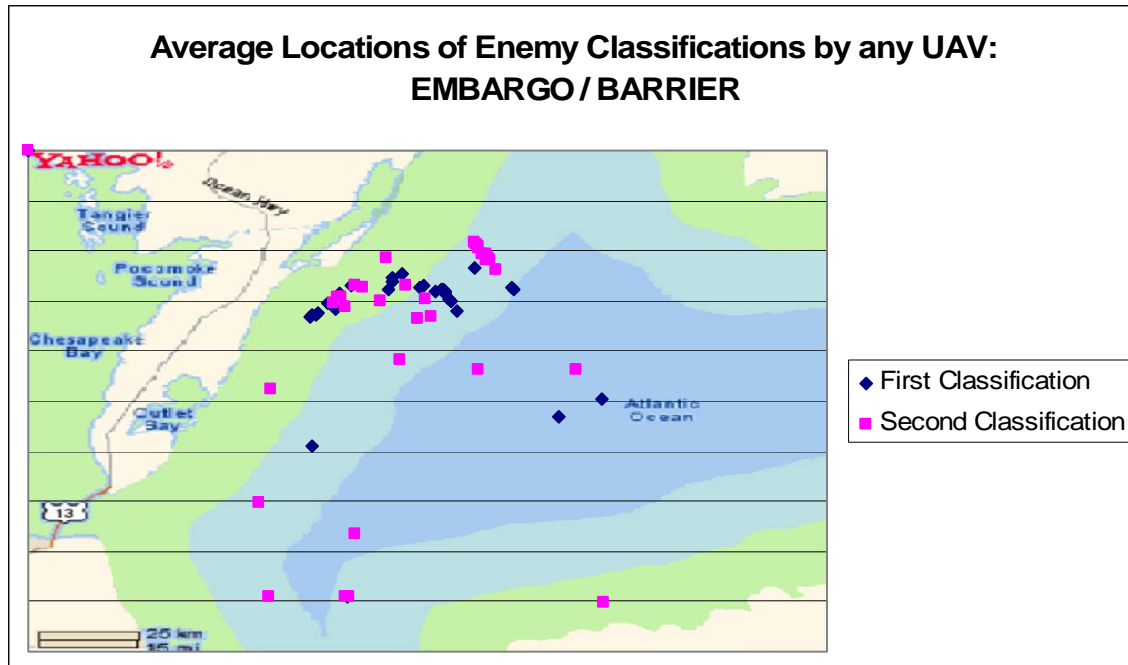
Figure 21: Average Locations of Enemy Classifications by any UAV for Embargo scenario with Blue "Barrier" tactic (best viewed in color)

Here again, most classifications are made in the northwest region. Outliers in the South tend to be the result of the BAMS alone, BAMS plus one, or single VTUAV combinations versus the Red "Combo" maneuver again. Since the scenario entails enemy contact maneuvers continuously toward the Southeast, classifications in the Northwest must occur earlier than classifications in the South. These earlier locations are desirable because they give the Blue force more time to react and interdict the Red force before arriving at their destination.

Blue forces with more UAVs make their classifications earlier, suggesting that having more UAVs is more effective. Note that in Figures 20 and 21, the second classification points in the extreme upper left position of the graphic indicate that no second classification was made. This point only occurs when a

VTUAV operates alone, showing a need to concurrently operate multiple UAVs.

These figures indicate that the different Blue tactics, "TSP" and "Barrier," did not significantly alter timeliness as depicted by the location of enemy classifications. This result may be attributed to the VTUAV flight paths not being altered with the change in Blue tactics—only the BAMS flight path was changed. As a result, the most significant result of changing Blue tactics is not the location of enemy classifications, but rather the reduction in the number of misses, which is included in the next section.

2. Completeness in Establishing the COP

Analysis of the average time to the second enemy classification adds further insight. The expectation is that BAMS should help to classify the remaining enemy contact since it has the ability to detect contacts in the whole area and can "break lock" from one enemy contact to go out and investigate others.

Figure 22 shows the average times to the second enemy classification by any UAV for the Embargo scenario with the Blue "TSP" tactic.
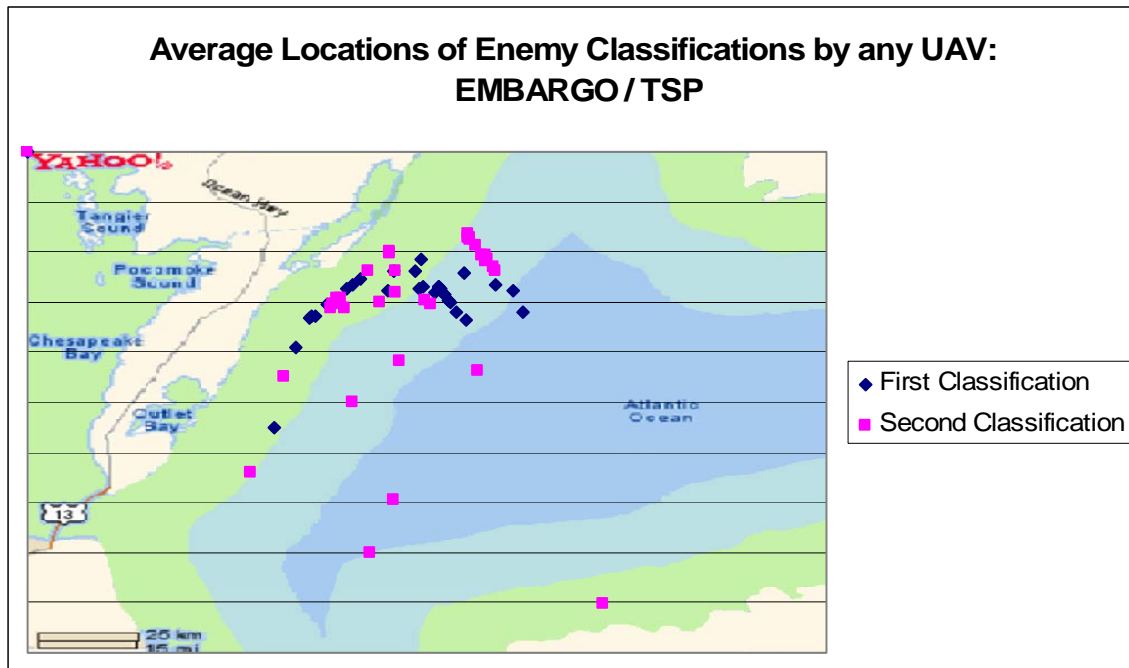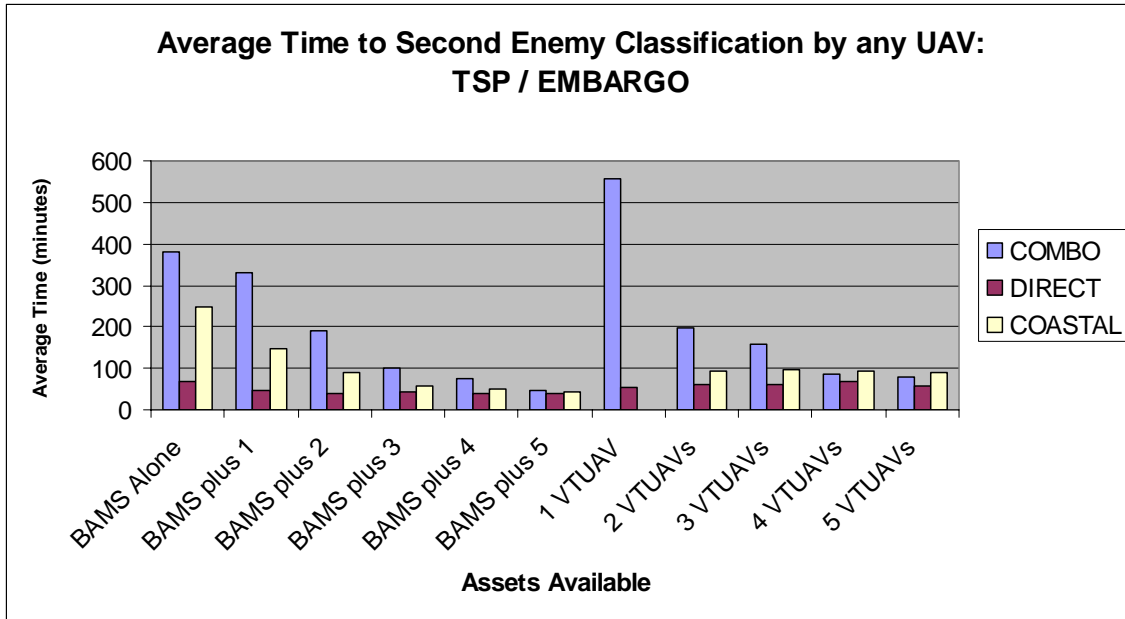
Figure 22: Average Time to Second Enemy Classification by any UAV for Embargo scenario with Blue "TSP" tactic (best viewed in color)

The average times to second enemy classification show that BAMS alone is better than one VTUAV, except in the "Direct" tactic where the results are similar. Again, for the Red "Coastal" maneuver, the one VTUAV combination misses the second enemy contact entirely, as it did with the first (see Figure 18). Figure 22 also shows that small numbers of VTUAVs do better when they operate without BAMS rather than with BAMS. This may indicate that there is some bias in the initial vectoring of the VTUAVs. Another possibility is simply that, as modeled, BAMS is not enhancing performance.

However, Figure 22 does show that BAMS provides shorter times to classification when more VTUAVs are added to the scenario. This point underscores the results from Figures 16-19 showing that the most efficient UAV combination is BAMS plus three VTUAVs and that the additional VTUAV does not always improve effectiveness.

These results differ from earlier results. In terms of a second enemy classification, the "Combo" maneuver is the most challenging Red maneuver for Blue to track. Tactically, this suggests that as the Red force splits up, the Blue force assets can get absorbed with one side of the operational area and have a more difficult time classifying both contacts on opposite ends of the maritime space. Unfortunately, this resembles real world operations as well.

The results for the second enemy classification when the Blue force employs the "Barrier" tactic are shown in Figure 23. These results turn out to be very similar to those shown in Figure 22.
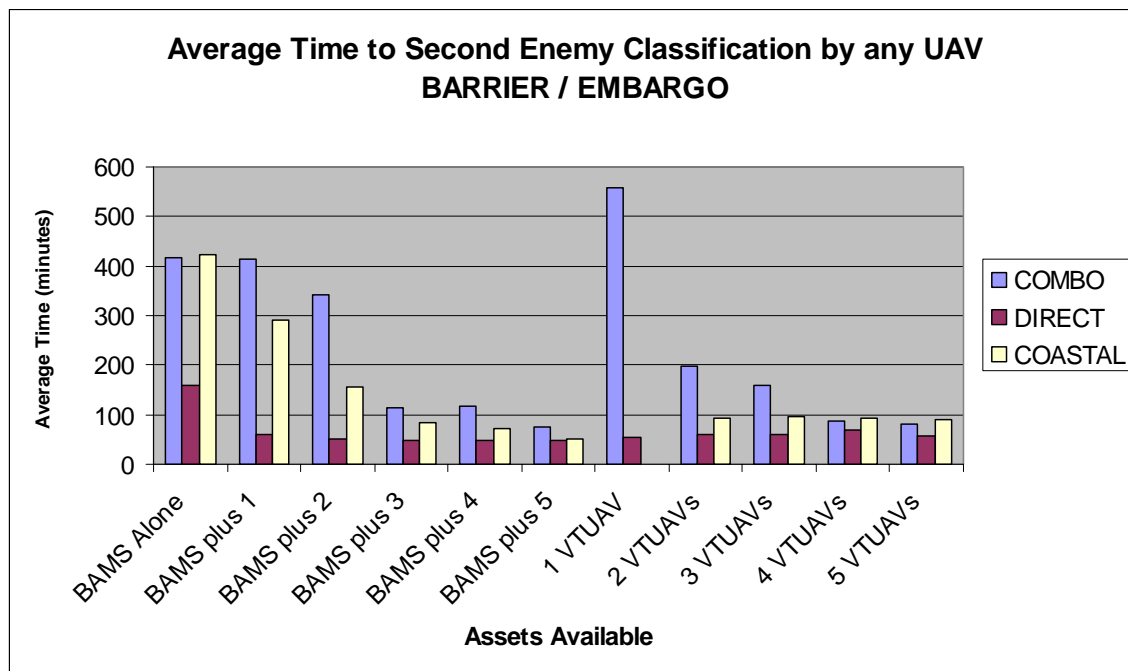
**Figure 23:** Average Time to Second Enemy Classification by any UAV for Embargo Scenario with Blue "Barrier" tactic (best viewed in color)

Naturally, for both Blue tactics, the average times to the second enemy classification are greater than the

average time to the first enemy classification. It is interesting that the times for both tactics are almost the same. Despite a more focused search by BAMS along the "Barrier," classification times remain the same. This indicates that BAMS tactics are less important. No matter where BAMS is in the space, its detection coverage can still reach to all areas of interest and can delegate identification assets to that region.

In addition to measuring completeness of the COP by looking at times to classify all Red forces, counting the number of leakers is also an important metric. Figure 24 shows the average proportion of misses for the Embargo scenario when the Blue force uses the "TSP" tactic.
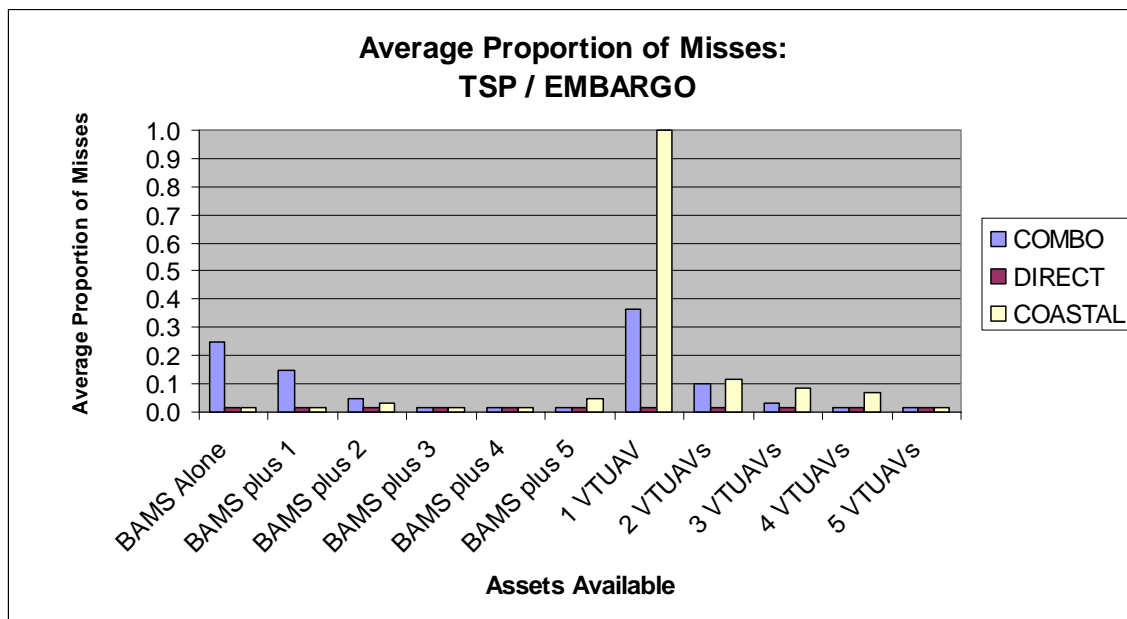
Figure 24: Average Proportion of Missed Enemy Classification for Embargo scenario with Blue "TSP" tactic (best viewed in color)

Although BAMS misses the occasional classification against the "Combo" tactic when it operates with fewer than two VTUAVs, its miss proportion is almost negligible when

operating with three or more VTUAVs. VTUAVs alone have problems with the "Coastal" maneuver and the "Combo" maneuver.

A single VTUAV provides the worst combination in terms of misses. In fact, when the Red force hugs the coastline, the single VTUAV always misses both Enemy ships in this simulation. These results are most likely due to the fact that without the presence of BAMS to point out where unidentified contacts are, a single VTUAV must rely only on its own, relatively short, sensor radius. Enemy ships that hug the coastline often escape this small sensor radius, resulting in more misses by the single VTUAV. With more VTUAVs, the assets can cover more area, but the chance of missing contacts entirely still exists. The number of misses is lowest when BAMS is present to detect all contacts initially, and can vector the VTUAVs in for identification.

Figure 25 depicts the average proportion of misses in the Embargo scenario for the "Barrier" tactic, which establishes a goal-keeping posture at the Red objective.
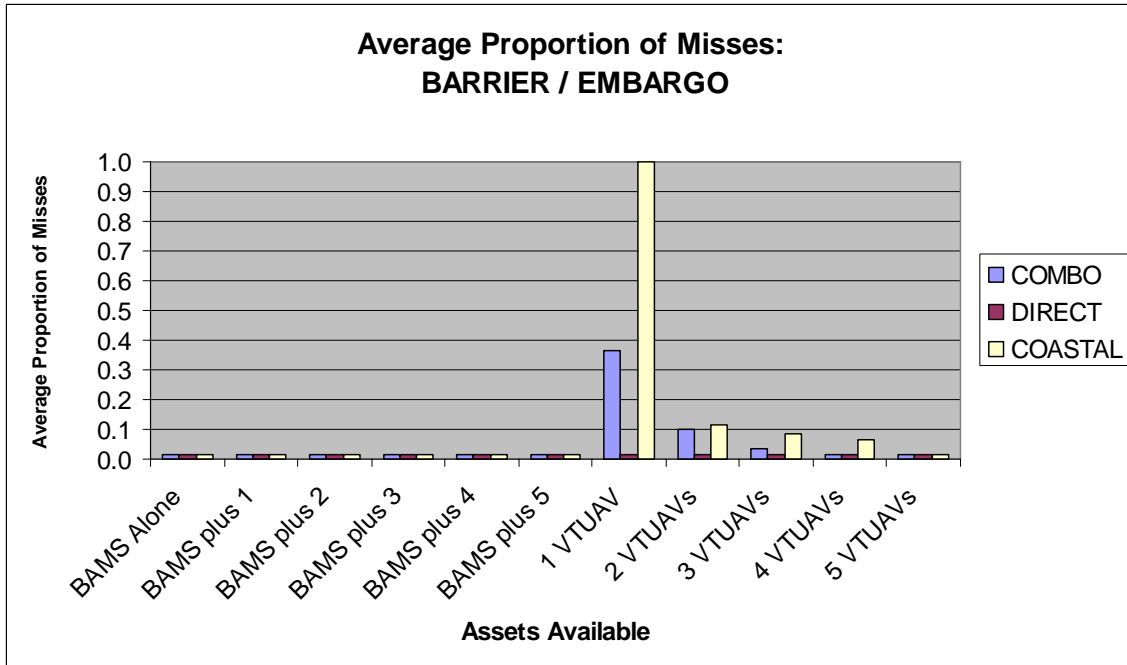
Figure 25: Average Proportion of Missed Enemy Classifications for Embargo scenario with the Blue "Barrier" tactic (best viewed in color)

Here, BAMS provides a larger payoff in terms of missed enemy classifications in the Embargo scenario. Every Blue force combination with BAMS does well against any Red force maneuver scheme. Misses are more likely without BAMS until five VTUAVs are available. Again, when a single VTUAV operates alone, it misses both enemy contacts against the "Coastal" maneuver.

Missed classifications data for both Blue tactics suggest that any combination with BAMS provides more capability for the Blue force. If no missed classifications are a requirement, then the "Barrier" tactic is probably optimal (although this tactic does result in longer times to first classification).

3. Classification Continuity on the COP

The last measure to be examined in the Embargo scenario is the proportion of time that each type of contact is positively identified when different UAV combinations and tactics are employed. This relates to how continuously the Blue force has an updated picture of what all contacts in the scenario are doing. The time is expressed as a proportion, dividing the average total number of time steps a contact is identified by the total number of time steps for the simulation run. To reiterate our expectations, BAMS should do especially well with regard to this measure since it has the capability to "break lock" and investigate other contacts, whereas the VTUAVs "pounce" on enemy ships for longer periods of time.

With regard to this operational objective, the Red "Combo" maneuver proved to be the most challenging again. In general, if the enemy ships move together along the coast or directly through the open ocean, any UAV combination tends to positively identify both contacts for nearly the same amount of time, due to proximity while revisiting. As discussed earlier, "Combo" also allows the enemy the most time for the second ship to evade classification, while the first ship absorbs the attention of any UAVs in the area. Although data is obtained and analyzed for all Red maneuvers, only the "Combo" tactic is presented in the following analysis because it is consistently the most challenging Red force presentation faced by the UAVs.

The average proportion of time that the enemy ships are positively identified when Blue employs the

"TSP" tactic against the Red "Combo" maneuver is plotted in Figure 26.
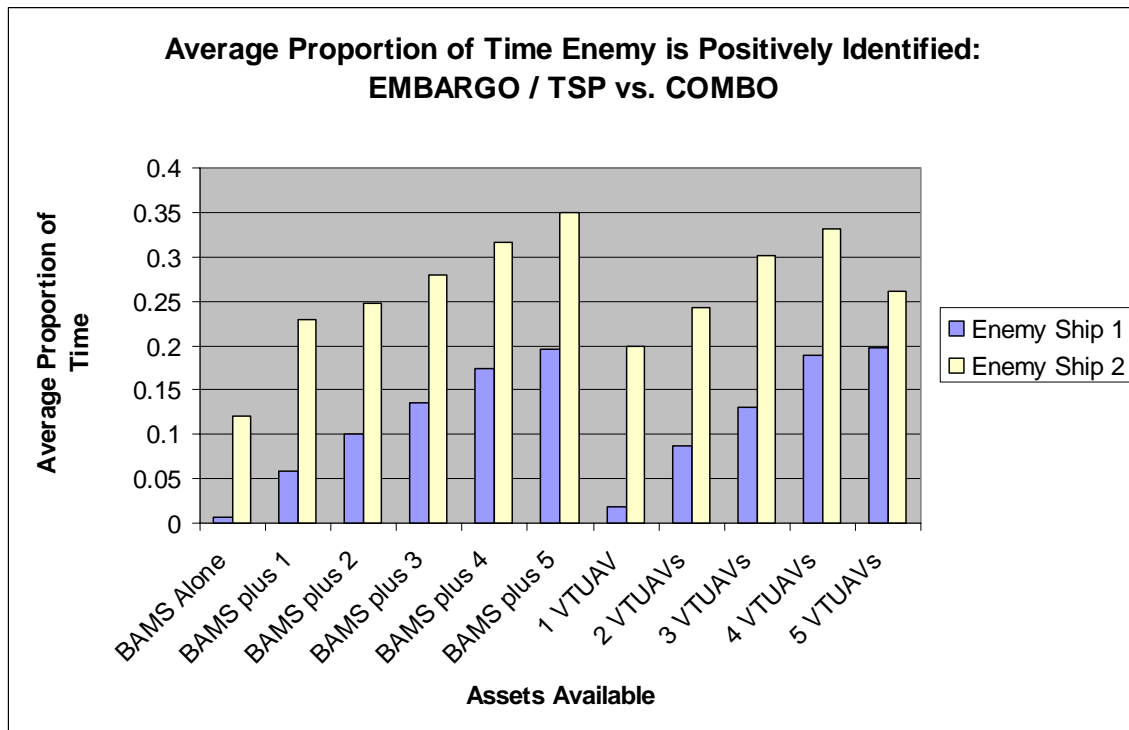
Figure 26: Average Proportion of Time Enemy is Positively Identified for Embargo scenario with Blue "TSP" and Red "Combo" maneuver scheme (best viewed in color)

The difference between times for Enemy Ship One and Enemy Ship Two is explained by the fact that Enemy Ship Two goes directly across the ocean and is easier to continuously monitor. The coastal ship, Enemy Ship One, is harder to track since UAVs are not allowed to penetrate territorial waters. This proximity to land masses restricts UAV motion and makes it more difficult to continuously monitor a coastal contact.

More significantly, the graph shows a 3%-5% increase in the proportion of time identified with the addition of each VTUAV, regardless of the presence of BAMS. This

increase also exists when the Blue force employs the "Barrier" tactic as shown in Figure 27.
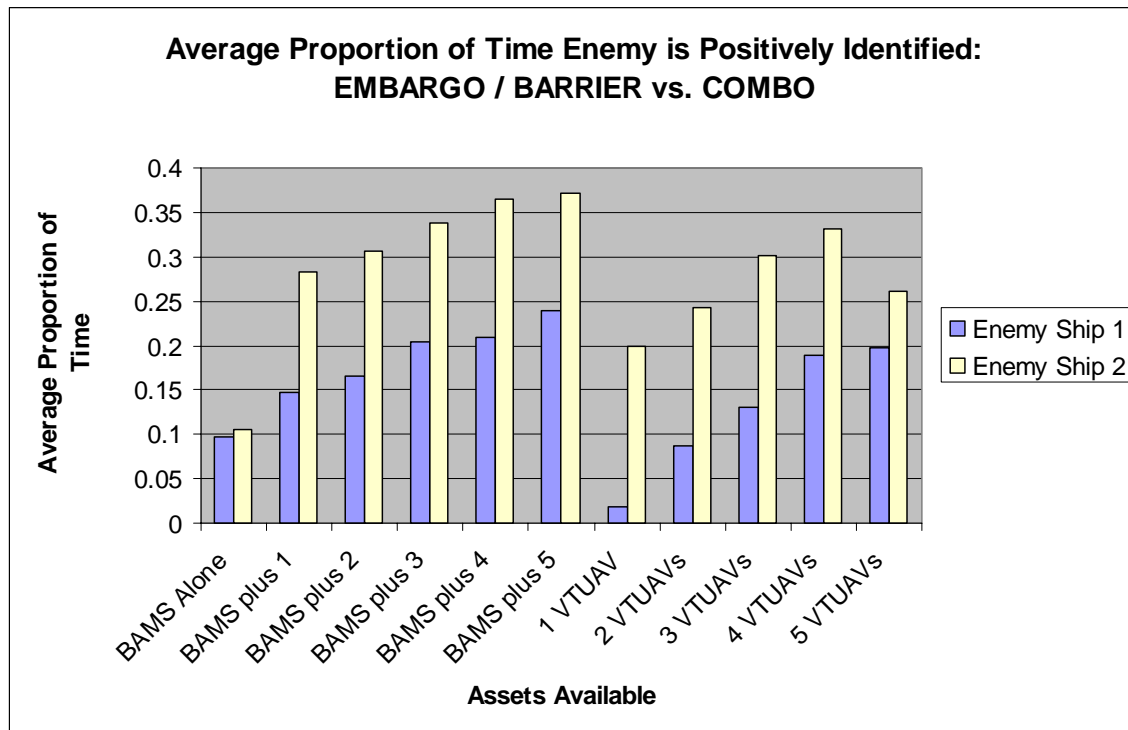
Average Proportion of Time Enemy is Positively Identified: EMBARGO / BARRIER vs. COMBO

Figure 27: Average Proportion of Time Enemy is Positively Identified for Embargo scenario with Blue "Barrier" and Red "Combo" maneuver scheme (best viewed in color)

A significant increase in the proportion of time that the Enemy Ship Two is identified is noticeable when one VTUAV is available to work with BAMS. The results also show higher proportions of time with BAMS than without BAMS. In general though, different Blue force tactics do not seem to greatly change the proportion of time that the enemy is positively identified.

The proportions of time that neutral contacts are positively identified are provided in Figures 28 and 29.
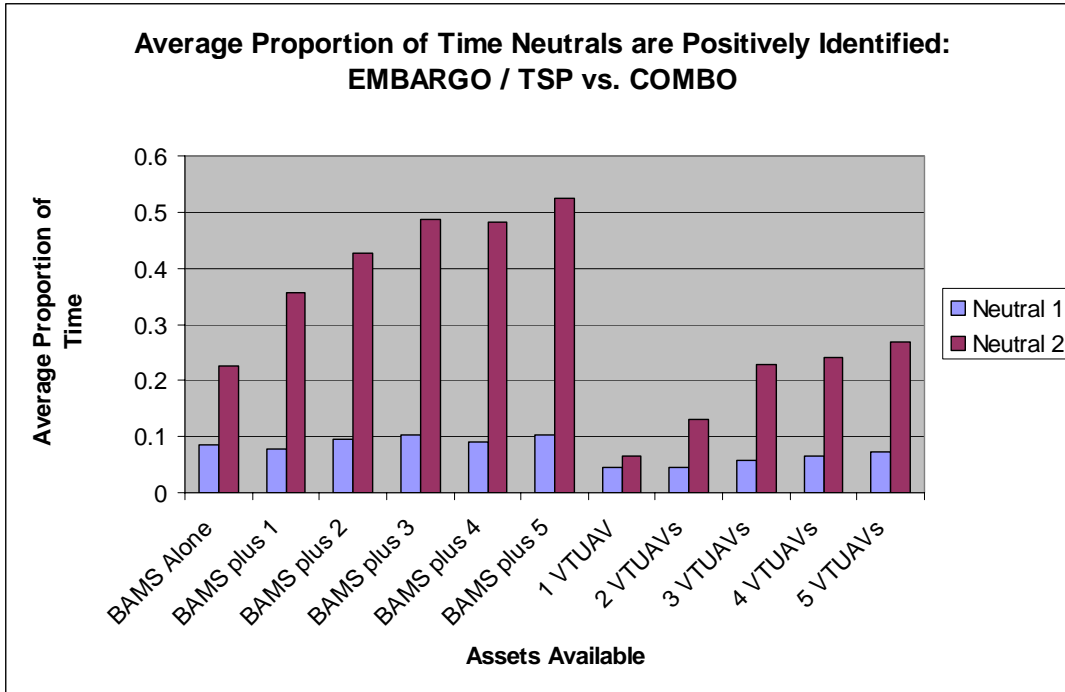
Figure 28: Average Proportion of Time Neutrals are Positively Identified in Embargo scenario with Blue "TSP" and Red "Combo" maneuver scheme (best viewed in color)
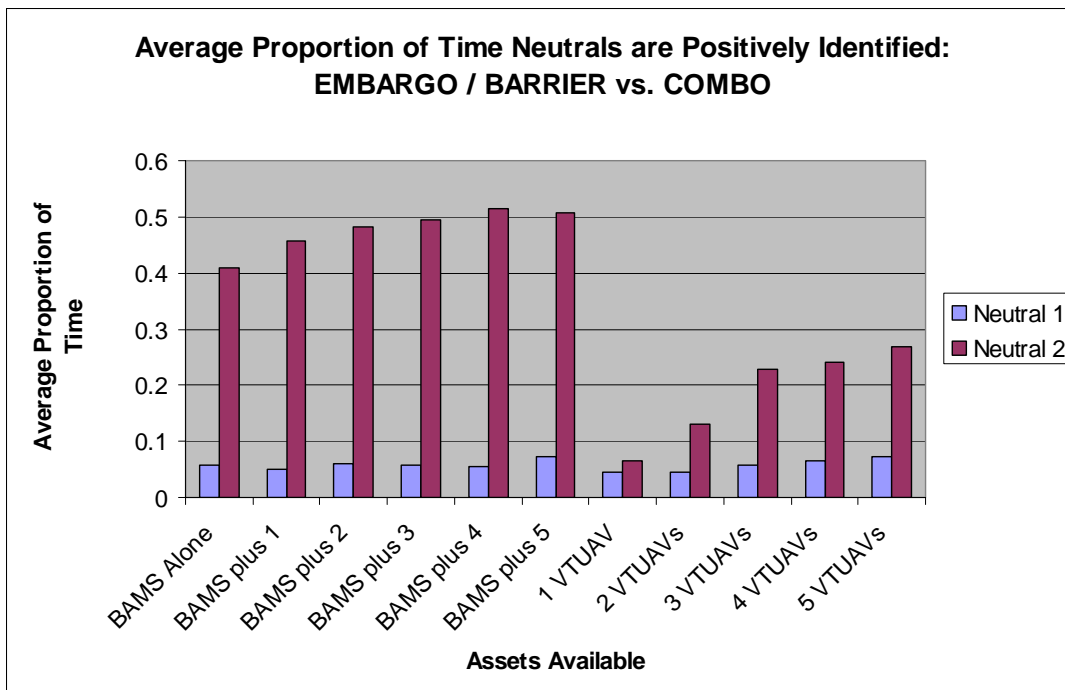
Figure 29: Average Proportion of Time Neutrals are Positively Identified in Embargo scenario with Blue "Barrier" and Red "Combo" maneuver scheme (best viewed in color)

BAMS provides a significant advantage with regard to the proportion of time that neutrals are identified for both Blue tactics. In general, there is a 20%-30% increase in the proportion of time that the Neutral 2 contact is monitored. The difference between Neutral 1 and Neutral 2 can be explained by the geographic location of each of these sets of vessels. The Neutral 1 ships start out moving away from BAMS in the shipping lane that is the farthest away. The Neutral 2 ships start out moving toward BAMS in the shipping lane that runs closest to where the enemy ships traverse.

The proportions of time that fishing vessels are positively identified is shown in Figure 30 for both the "TSP" and "Barrier" tactics.
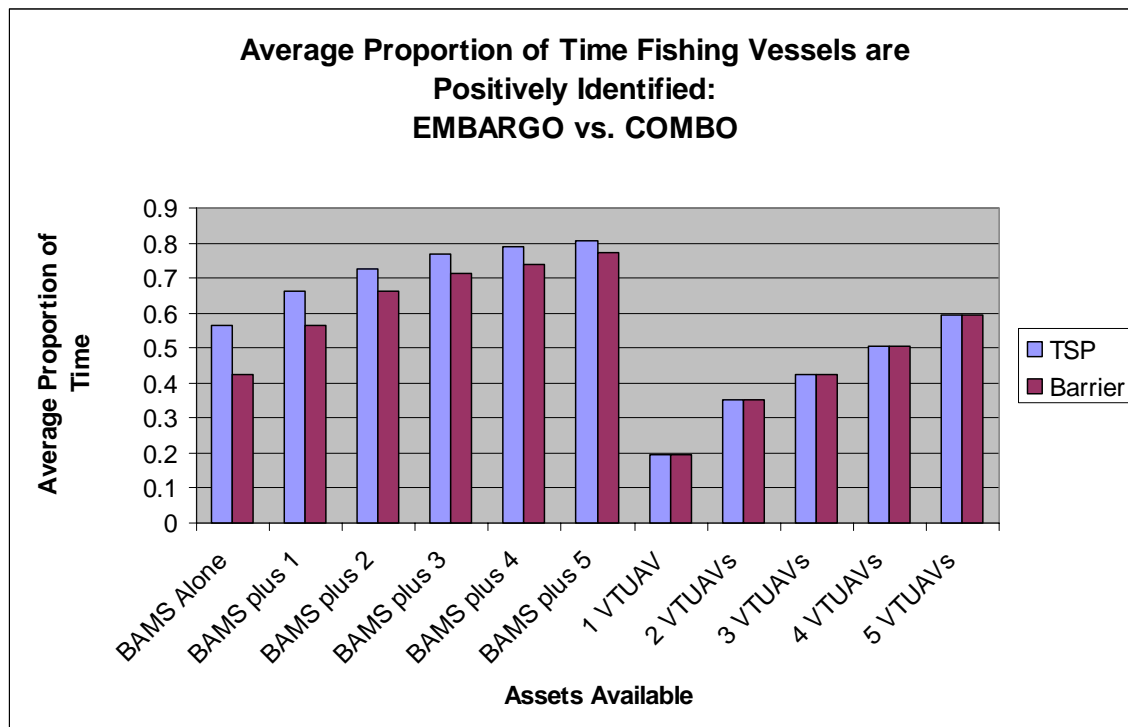
Figure 30: Average Proportion of Time Fishing Vessels are Positively Identified in Embargo scenario with Blue "TSP" and "Barrier" tactics versus Red "Combo" maneuver scheme (best viewed in color)

Here again, UAV combinations with BAMS provide a substantial (10%-30%) increase in the proportion of time that contacts are identified versus UAV combinations without BAMS. The aggregate results for the average proportion of time that contacts are positively identified show that BAMS provides a significant advantage in terms of monitoring all types of contacts throughout the operational area.

Figures 28-30 also show that as the number of available VTUAVs increases, the average proportions of time increase. This increase appears to be linear in the absence of BAMS. In the presence of BAMS, increases in the average proportion of time positively identified diminish as the number of VTUAVs increases beyond three. This decreasing marginal return is depicted in Table 9 with regard to the monitoring of fishing vessels.

Asset Combination	% Increase in Proportion of Time Fishing Vessels are Positively Identified per Additional VTUAV (Slope)
BAMS alone	0.0966
BAMS plus 1	0.0633
BAMS plus 2	0.0419
BAMS plus 3	0.0209
BAMS plus 4	0.0195

Table 9: Diminishing returns with the addition of more VTUAVs with regard to the time Fishing vessels are positively identified

This suggests that the payoff of additional VTUAVs in the presence of BAMS decreases between two or three VTUAVs. The ability of BAMS to enable Blue forces to keep track of neutral and uninteresting contacts prevents wasting resources by revisiting these tracks. This is an essential function in focusing Intelligence Surveillance and

Reconnaissance (ISR) assets on critical contacts of interest.

B.   ASSURED ACCESS RESULTS

1.   Timeliness in Establishing the COP

As in the Embargo scenario, combinations with BAMS are expected to out-perform combinations without BAMS in the Assured Access scenario.   To determine timeliness is establishing the COP, we analyze the average times to first enemy classification when the Blue force uses the "TSP" tactic and the Red force uses the "All Small" maneuver scheme in Figure 31.   The maneuver scheme is selected since it serves as a good baseline for later analysis.
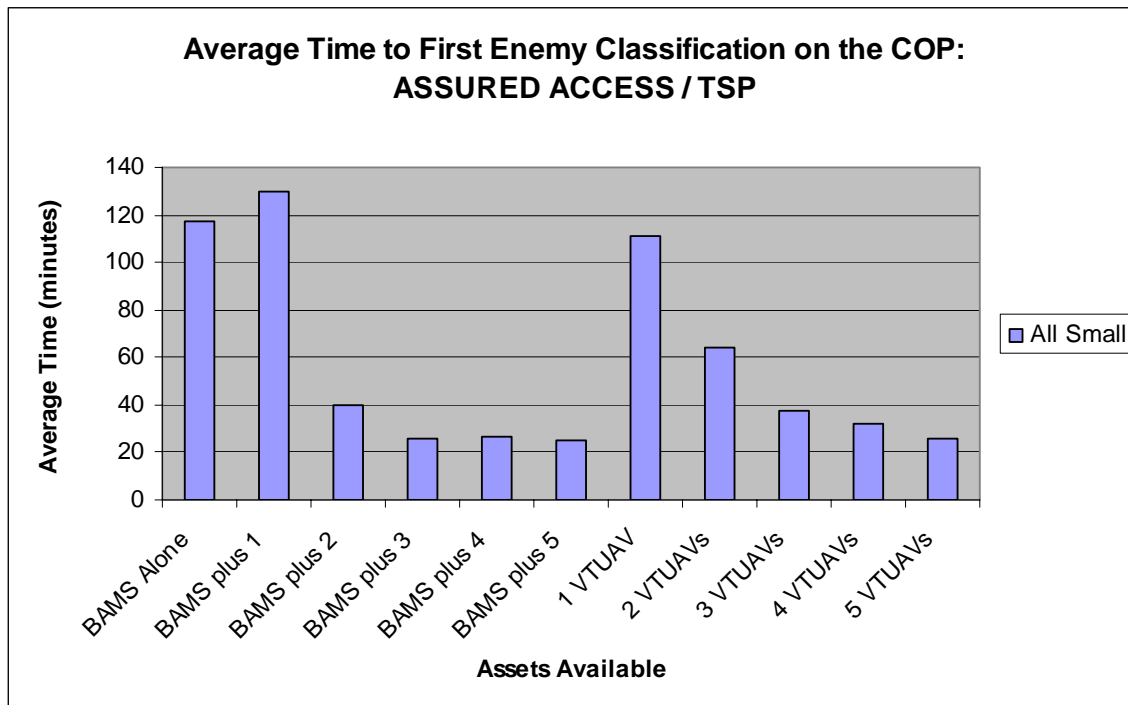
Figure 31: Average Time to First Enemy Classification on the COP in Assured Access scenario with Blue "TSP" and Red "All Small" maneuver scheme (best viewed in color)

For the Assured Access scenario, times to first classification diminish rapidly when two VTUAVs are available, regardless of the presence of BAMS. This result is nearly the same as in the Embargo scenario, except that the "knee in the curve" appears to be at two VTUAVs instead of three VTUAVs, as in the Embargo scenario. Moreover, BAMS alone and BAMS plus one VTUAV combinations perform worse than one VTUAV alone or two VTUAVs alone.

Upon examination of the model, it seems that these results are due to the model's propensity, discussed earlier, for VTUAVs to move away from each other, pushing the VTUAVs toward more remote parts of the area and enabling them to make contact with the northernmost enemy ship faster. The VTUAV's air speed is also slow enough to give the red enemy ship time to drive closer to it after BAMS passes the same region. Because BAMS enters the region faster, it tends to focus on other unknown contacts before the northernmost enemy ship progresses into the center of the operational area.

The box and whisker plot of this data (Figure 32) provides further insight.
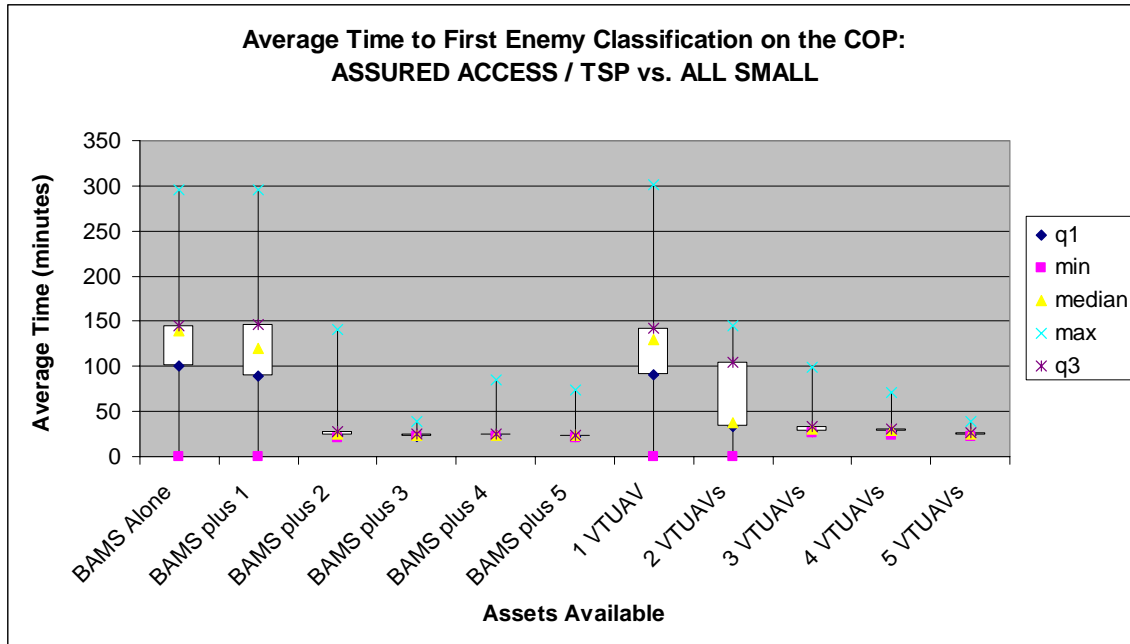
Figure 32: Box and Whisker plot of average time to first enemy
classification on the COP in Assured Access scenario for
Blue "TSP" tactic and Red "All Small" maneuver scheme
(best viewed in color)

This plot confirms performance differences among
combinations with smaller amounts of VTUAVs and
combinations with larger amounts of VTUAVs. It also
suggests that the differences in the distributions between
the combinations of BAMS alone or BAMS plus one VTUAV and
the combinations of one or two VTUAVs alone is not that
significant (the inter-quartile ranges overlap).

Of interest in this plot is the comparison with
BAMS plus two or more VTUAVs against combinations of three
or more VTUAVS alone. Each has the same concentrated
distributions of just below 36 minutes. This suggests that
perhaps three VTUAVs are just as effective as BAMS and
two VTUAVs. Multiple t-tests are performed on this data to
see if this is indeed the case.

Table 10 shows the results of the t-test, which
compares BAMS plus three VTUAVs and three VTUAVs alone for

the Assured Access scenario with the "TSP" and "All Small" tactics. These tests show that although the distributions look similar, it is possible to say that there is a statistically significant difference between BAMS plus three or more VTUAVs and three or more VTUAVs alone at less than the .001 level.

t-test: Two-Sample Assuming Unequal Variances

	BAMS + 3	3 VTUAVs
Mean	25.62	37.60
Variance	17.24	332.48
Observations	30.00	30.00
Hypothesized Mean Difference	0.00	
df	32.00	
t Stat	-3.51	
P(T<=t) one-tail	0.000679	
t Critical one-tail	1.69	
P(T<=t) two-tail	0.001358	
t Critical two-tail	2.04	

Table 10: t-test between BAMS plus three VTUAVs and three VTUAVs alone in Assured Access scenario with Blue "TSP" tactic and Red "All Small" maneuver scheme

The p-values indicate a three-in-one-thousand chance of seeing the results if there were no difference in performance. Because this is so unlikely, we conclude that in the Assured Access scenario, this UAV combination with BAMS and higher numbers of VTUAVs is more effective than a combination without BAMS. The amount of improvement is roughly equal to the difference in means, or 12 minutes.

Since the next closest combination is BAMS plus two VTUAVs t-test, another t-test, shown in Table 11, compares BAMS plus two VTUAVs and BAMS plus three VTUAV combinations.

t-test: Two-Sample Assuming Unequal Variances

	BAMS + 2	BAMS + 3
Mean	39.60	25.62
Variance	1159.94	17.24
Observations	30.00	30.00
Hypothesized Mean Difference	0.00	
df	30.00	
t Stat	2.23	
P(T<=t) one-tail	0.0166	
t Critical one-tail	1.70	
P(T<=t) two-tail	0.0333	
t Critical two-tail	2.04	

Table 11: t-test between BAMS plus two VTUAVs and BAMS plus three VTUAVs for the Assured Access scenario with Blue "TSP" tactic and Red "All Small" maneuver schemes

Because the p-values are again less than 0.05, we can reject the null hypothesis that the two distributions have the same mean. In fact, the BAMS plus three combination, with a mean time to first classification of 25.62 minutes, is better than the BAMS plus two combination with a mean of 39.6 minutes. This is a difference of roughly 14 minutes. We also see much less variability in BAMS plus three with a variance of 17.24 versus the much larger variance of 1159.94 for BAMS plus two. Therefore, the addition of three VTUAVs to BAMS seems to be enough to provide the most efficient and consistent results; but, on average, this combination is only about 14 minutes faster than the next best combination——BAMS plus two VTUAVs. Here again, the significance of this amount of time is scenario dependent. In an urgent response operation, every minute counts, whereas in steady state maritime search, 13-30 minute increments are probably operationally insignificant.

The end result of these t-tests is that for the Assured Access scenario with the Blue "TSP" and Red "All Small" tactic, combinations with BAMS do provide a benefit. But this may not be significantly beneficial when

compared to performance of a force with additional VTUAVs without BAMS. A tactic in which VTUAVs move away from each other enables exploration of the whole area and makes up for the added benefit of contact detection by BAMS.

a.   Effect of Tactics and Maneuvers on Classification Timeliness

Figure 33 shows what happens when other Red force maneuvers are employed in the Assured Access scenario.
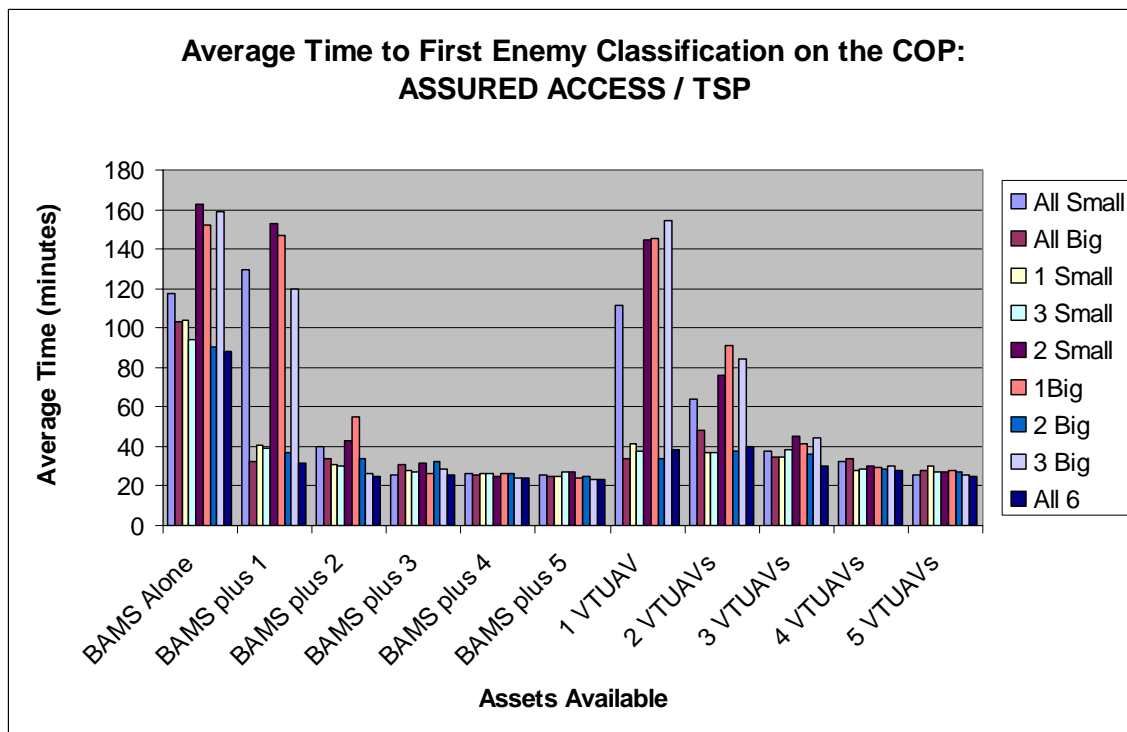
Figure 33: Average Time to First Enemy Classification on the COP for Assured Access scenario with Blue "TSP" tactic versus all types of Red maneuver schemes (best viewed in color)

Figure 33 shows that results described earlier are relatively robust against Red force maneuvers. Blue force actions and numbers drive performance regardless of the Red scheme considered. The "knee in the curve" between performance and the addition of more VTUAVs seems to exist between the two through three VTUAV points for all tactics. As the number of VTUAVs increases, combinations with BAMS

provide faster times to classification, although only on the order of 18 minutes or less. The VTUAVs' propensity to move away from each other enables them to explore the whole operational area faster and makes up for the added benefit of contact detection by BAMS.

Figure 34 shows what happens to this data then the Blue tactic is changed from "TSP" to the "Barrier" tactic.
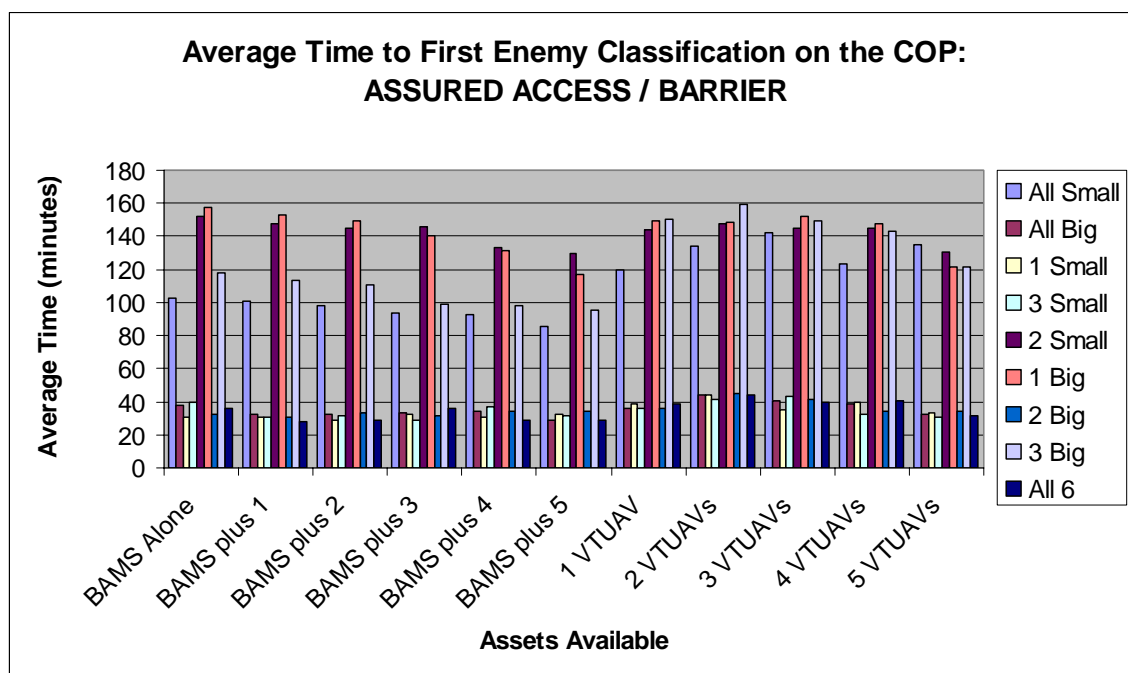
Figure 34: Average Time to First Enemy Classification on the COP in Assured Access scenario with Blue "Barrier" tactic versus all types of Red maneuver schemes (best viewed in color)

There is a wide range of initial classification times based upon various Red maneuvers. In contrast to the "TSP" tactic, no UAV combination seems to provide a real advantage over any other. Therefore, with respect to the time to first enemy classification, Blue tactics sometimes matter in the Assured Access scenario. If the "TSP" tactic is employed, then the Blue force should employ at least

two VTUAVs with BAMS. If the "Barrier" tactic is desired, the number of VTUAVs is less important. However, since the maximum and minimum times to first classification are nearly the same for both tactics, the tactical difference with respect to this measure is fairly insignificant.

b.   *Classification Location as an Indication of Timeliness*

As in the Embargo scenario, classification locations are an important measure of tactics in terms of the amount of time that the Blue force has to react to the presence of any hostiles. Figure 35 shows these locations for the Assured Access scenario when BAMS employs the "TSP" tactic, depicting the average distribution of locations and providing insight into classification trends.
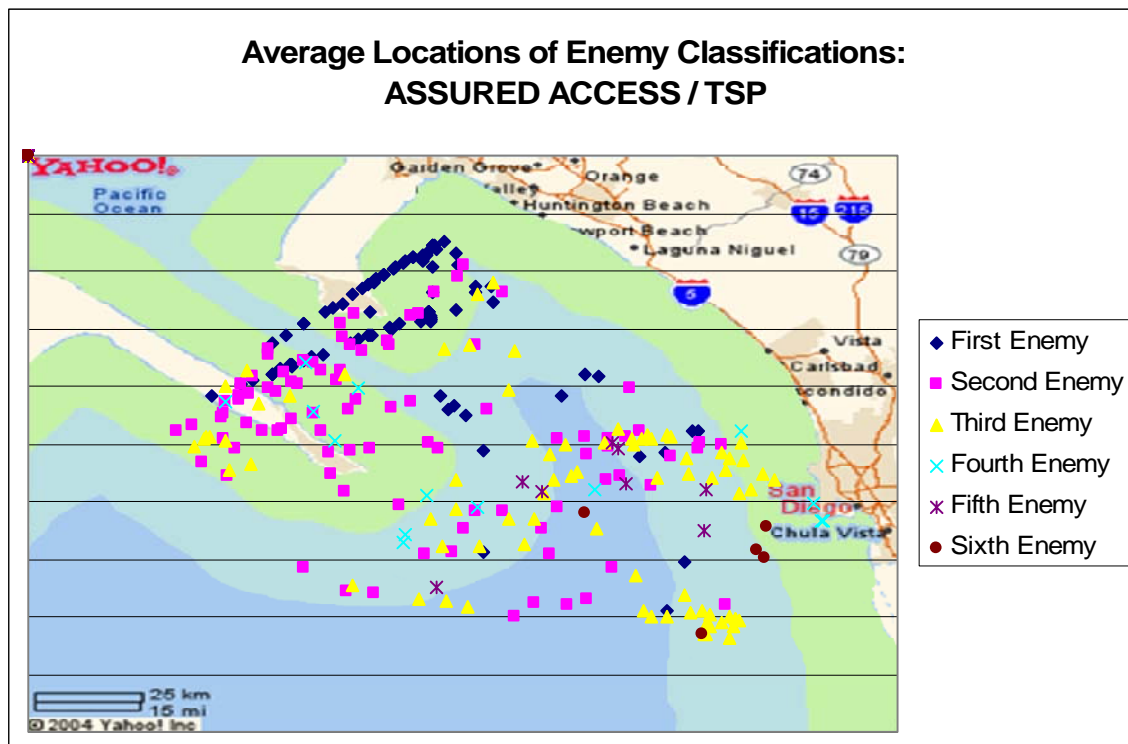
Figure 35: Average Locations of Enemy Classifications for Assured Access scenario with Blue "TSP" tactic (best viewed in color)

Figure 35 provides a general feel for the frontier of initial classifications. For instance, the first classification normally occurs in the northwest region of the operational area. This region also has a higher distribution of second classifications. The third classification is normally more toward the southeast. The locations depicted are averages, so it is possible for them to show up in positions that do not make sense, such as over land.

In comparison, the results for the same scenario when BAMS employs the "Barrier" tactic are shown in Figure 36.
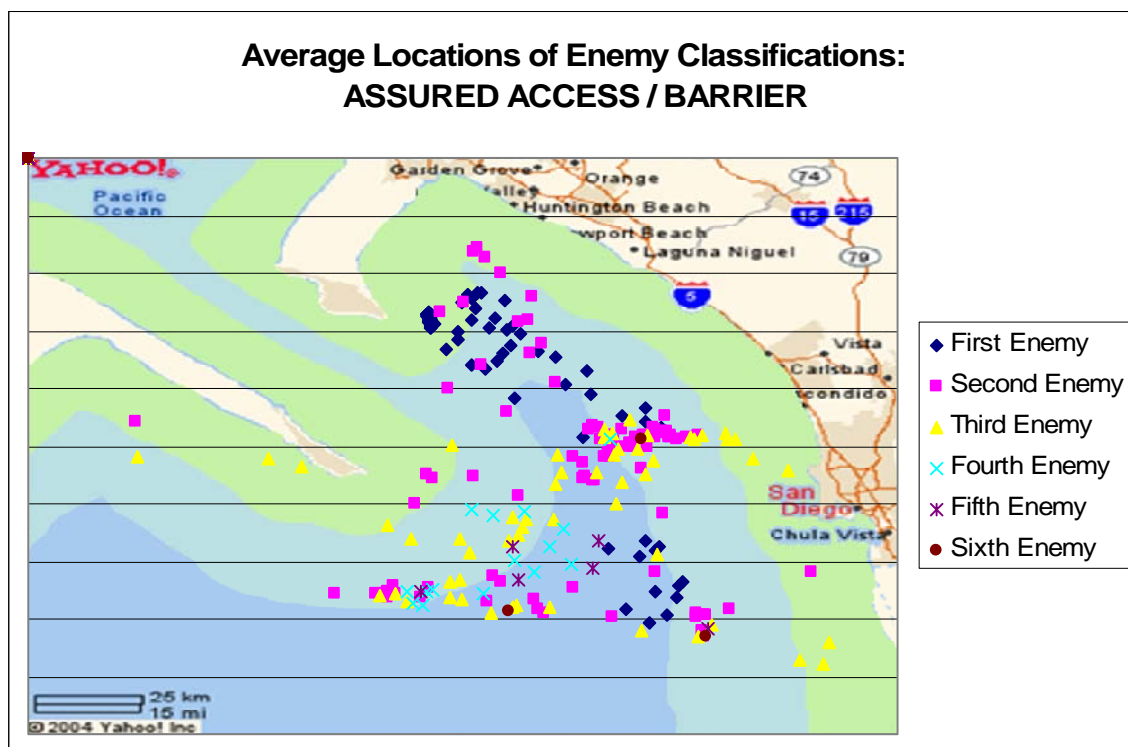
Figure 36: Average Locations of Enemy Classifications with Blue "Barrier" tactic (best viewed in color)

Now the first enemy classifications occur deeper in the area of interest toward the northeast and sometimes

in the southeast. In general, fewer classifications occur in the northwest quadrant.

Based upon these figures, tactical choices will depend upon Blue force mission urgency and destination location. The "TSP" tactic provides more classifications upon initial entry into the gulf-like region, but the "Barrier" tactic provides more classifications along the specific Blue force track.

If the Blue force is conducting steady-state operations and is purely trying to enter the gulf region to survey the area, then "TSP" is probably a better choice. With "TSP," the Blue force is alerted to the enemy presence throughout the frontier zone. With less time constraints, the force can spend more time gathering information on interesting contacts in this area, while it is less concerned about the whole interior of the region.

However, if the Blue force is conducting a time-critical operation and is trying to expeditiously get to a northeastern or northwestern objective inside the gulf, then the "Barrier" is probably best. While not surveying the entire frontier zone, this tactic does allow the Blue force to penetrate the area right in front of the Blue force track more effectively.

2.   Completeness of the COP

Due to the nature of the Assured Access mission, minimizing the number of leakers is most important. If the COP is not complete, and an enemy is missed, the security of an advancing Blue force may be put in jeopardy. Again, the expectation is that BAMS should be a force multiplier with respect to this measure, with its broad area surveillance capabilities and high speed. Figure 37 shows

the average number of misses for the Assured Access scenario when the "TSP" tactic is employed.
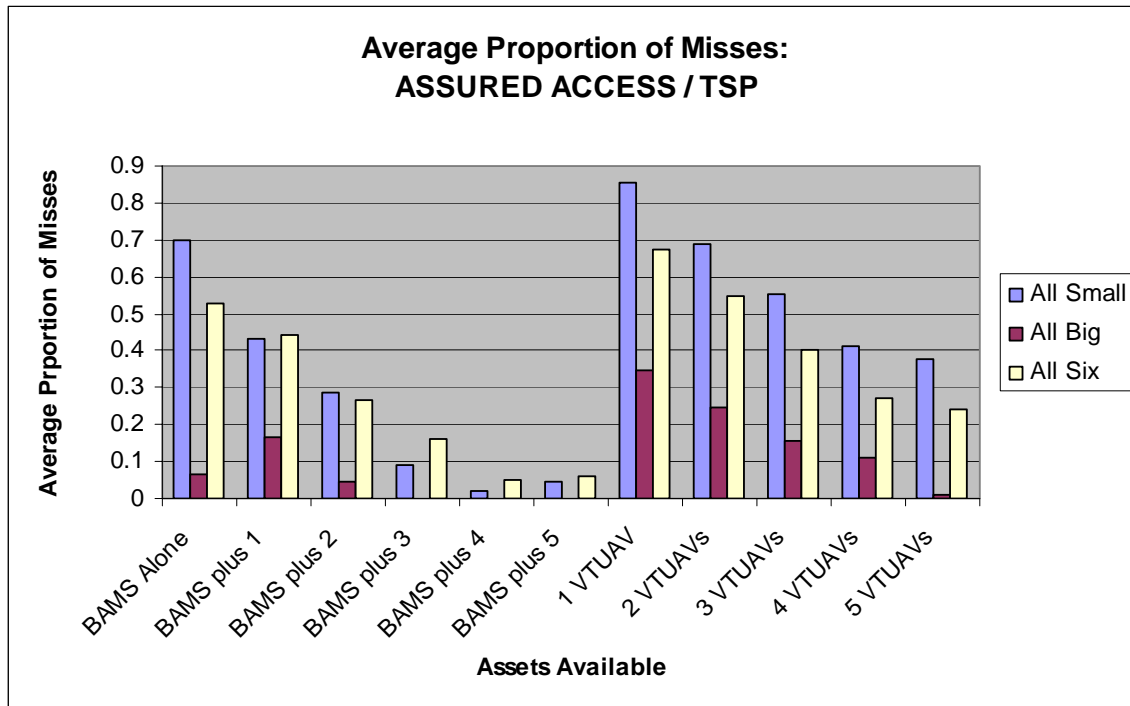
Figure 37: Average Proportion of Missed Enemy Classifications for Assured Access scenario with Blue "TSP" tactic (best viewed in color)

As in the Embargo scenario, employing BAMS decreases miss rates in the Assured Access scenario. Blue forces are most effective at completely developing the COP when the Red force is more adventurous, as in the "All Big" maneuver scheme. This result makes sense in that it is typically easier for contacts to be classified when they are in the middle of the area. It is harder for UAVs to explore all the extreme corners of the maritime space when other contacts in the center require classification as well.

Figure 38 shows similar results for the "Barrier" tactic. Here, the results are not as good since BAMS focuses its search along the projected Blue force track, but the number of misses with BAMS is still lower

than without BAMS. Again, Blue forces are most effective at completely developing the COP when the Red force is more adventurous, as in the "All Big" maneuver scheme.
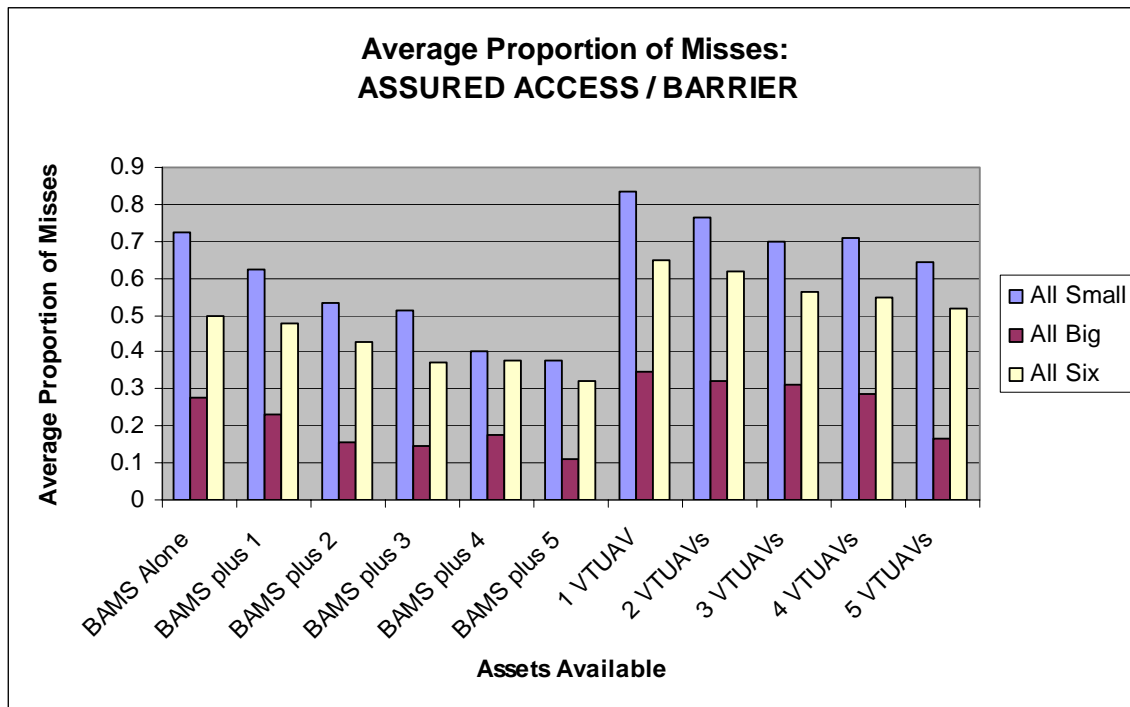
Figure 38: Average Proportion of Missed Enemy Classifications for Assured Access scenario with Blue "Barrier" tactic (best viewed in color)

In general, there are higher numbers of misses for Blue forces against larger-scale Red forces patrolling on all possible patrol routes (i.e. in the "All Six" maneuver scheme). Because of the large scale opposition, it is difficult for VTUAVs to split coverage time among each of them. The VTUAVs are "pouncers" and are more inclined to stay with enemy contacts after they are identified, while the benefits of BAMS could further increase as the number of enemy contacts increases beyond this range. Despite changes in Blue force tactics and Red force maneuvers, BAMS consistently enables fewer leakers.

3. Classification Continuity on the COP

The last measure to be examined in the Assured Access scenario is the proportion of time that each type of contact is positively identified when different UAV combinations and tactics are employed. The proportion results from dividing the average amount of time contacts are identified by the total number of time steps in the simulation.

As in the Embargo scenario, we expect combinations with BAMS to outperform combinations with VTUAVs alone since it has "break lock" ability and the broad area MS radar.

With regard to this measure and the nine types of enemy tactics, only the "All Small," "All Big," and "All Six," tactics are presented in the analysis, as they provide the widest ranges of variability and displacement of enemy ships. The results for the "All Small" tactic versus the Blue force "TSP" tactic are shown in Figure 39. For this configuration, Enemy ships 1, 2, and 3 each start out at different geographic locations in the Southeast, Northeast, and Northwest, respectively.

Average Proportion of Time Enemy is Positively Identified: ASSURED ACCESS / TSP vs. ALL SMALL

Figure 39: Average Proportion of Time Enemy is Positively Identified in Assured Access scenario with Blue "TSP" tactic and Red "All Small" maneuver scheme (best viewed in color)

Of major importance here is that all enemies are positively identified only when BAMS is present. In the absence of BAMS, Enemy 1 is never tracked for any length of time. Also of interest is that when BAMS operates alone, it does a poor job of tracking any contact. BAMS tends to get distracted with other contacts and does not "pounce" on them for long periods of time. Similar results are obtained when the Blue force uses the "Barrier" tactic, as shown in Figure 40.

Average Proportion of Time Enemy is Positively Identified: ASSURED ACCESS / BARRIER vs. ALL SMALL

Y-axis: **Average Proportion of Time** (0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3)

X-axis: **Assets Available** (BAMS Alone, BAMS plus 1, BAMS plus 2, BAMS plus 3, BAMS plus 4, BAMS plus 5, 1 VTUAV, 2 VTUAVs, 3 VTUAVs, 4 VTUAVs, 5 VTUAVs)

Legend: Enemy 1, Enemy 2, Enemy 3

Figure 40: Average Proportion of Time Enemy is Positively Identified in Assured Access scenario with Blue "Barrier" tactic and Red "All Small" maneuver scheme (best viewed in color)

When Red forces stay back in a defensive posture (as in the "All Small" maneuver), BAMS provides a significant advantage regardless of Blue force tactics. But BAMS does need to operate with at least one other VTUAV in order to be effective.

The results for the "All Big" maneuver versus the "TSP" tactic are shown in Figure 41.

Figure 41: Average Proportion of Time Enemy is Positively Identified in Assured Access scenario with Blue "TSP" tactic and Red "All Big" maneuver scheme (best viewed in color)

The proportion of time for Enemy 2, in the Northeast, and Enemy 3, in the Northwest, are roughly the same regardless of the presence of BAMS. However, the proportion of time that Enemy 1, in the Southeast, is covered increases significantly when BAMS is available. The same results are less noticeable when the Blue force employs the "Barrier" tactic (as shown in Figure 42), but BAMS still provides a small advantage with respect to coverage of Enemy 1. Therefore, BAMS is also a valuable asset against the "All Big" Red maneuver for both Blue tactics.
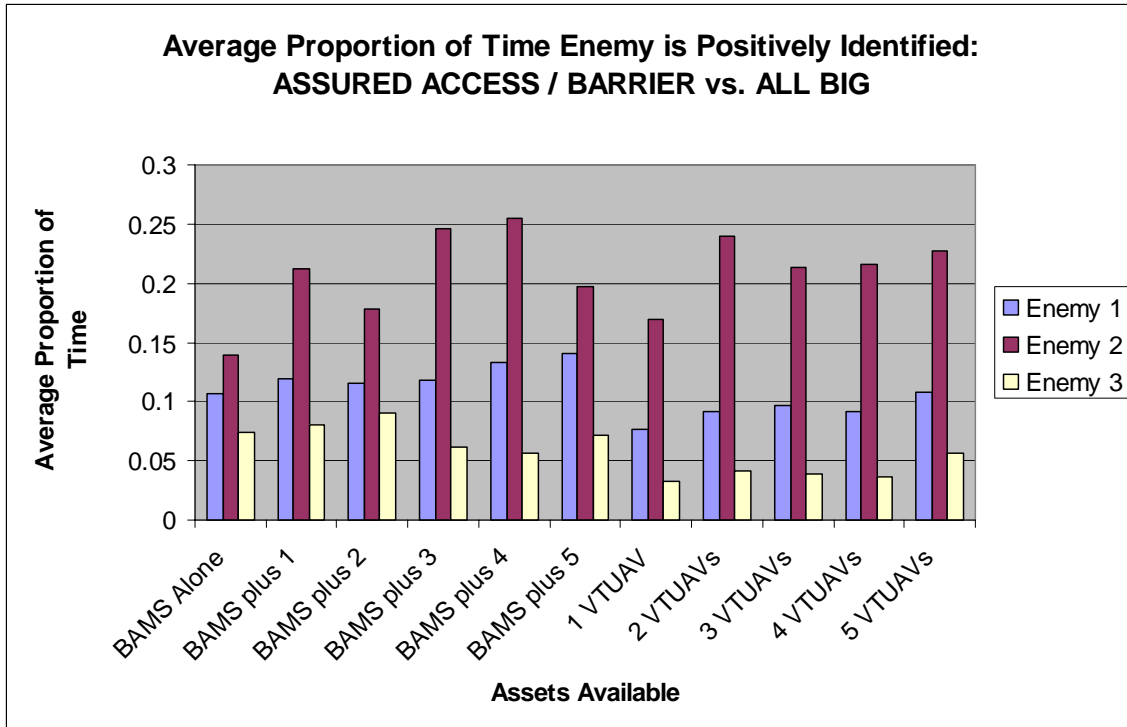
Figure 42: Average proportion of time Enemy is Positively Identified in Assured Access scenario with Blue "Barrier" tactic and Red "All Big" maneuver scheme (best viewed in color)

As opposed to the defensive Red force maneuvers, Blue forces are more effective when Red forces are more aggressive. This improvement makes sense. Against the "All Small" Red maneuver scheme, UAVs must fly farther and investigate the extremes of the operational area in order to track all contacts. With the "All Big" scheme, the enemies move further into the center of the maritime space where they are easier to track.

Results when the enemy floods the gulf region with multiple contacts in the "All Six" maneuver scheme versus "TSP" are shown in Figure 43.
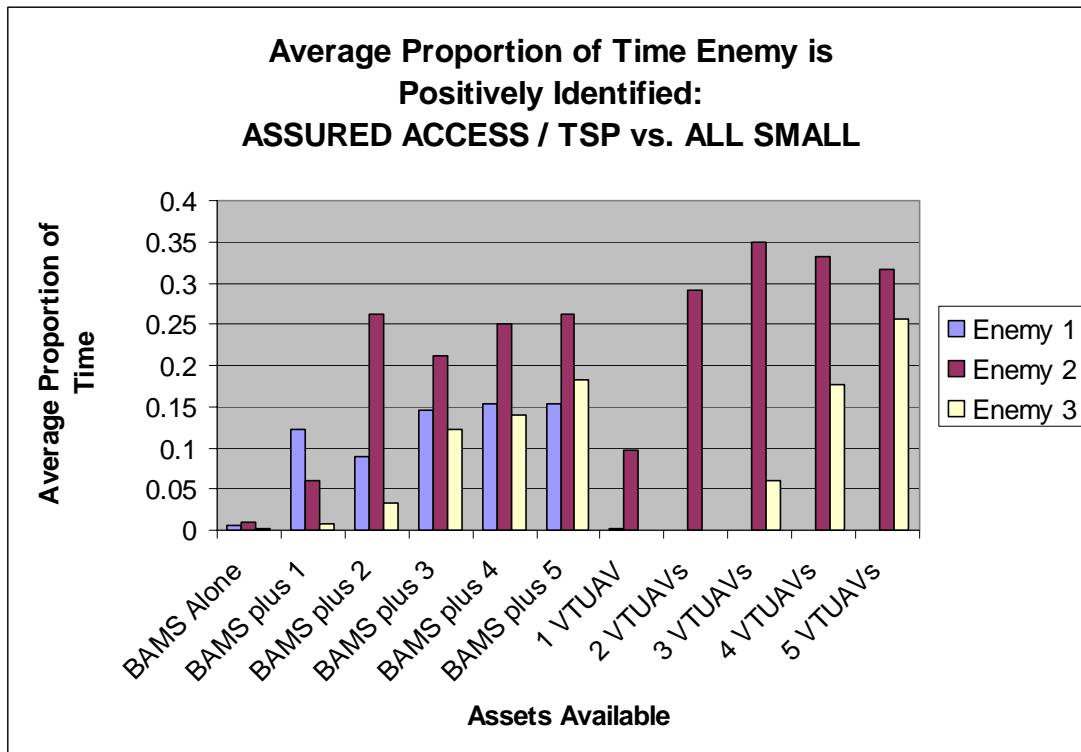
Figure 43: Average Proportion of Time Enemy is Positively Identified in Assured Access scenario with Blue "TSP" tactic and Red "All Six" maneuver scheme (best viewed in color)

Figure 43 shows that more enemies are positively identified for longer periods of time with BAMS present, although this is still very much subject to Red force activity. In the cases of one to three VTUAVs alone, the VTUAVs pounce on one enemy (Enemy 4), and the rest of the enemy ships are positively identified less. BAMS seems to provide more versatility when it comes to monitoring all contacts. Figure 44 shows similar results when the Blue force employs the "Barrier" tactic.
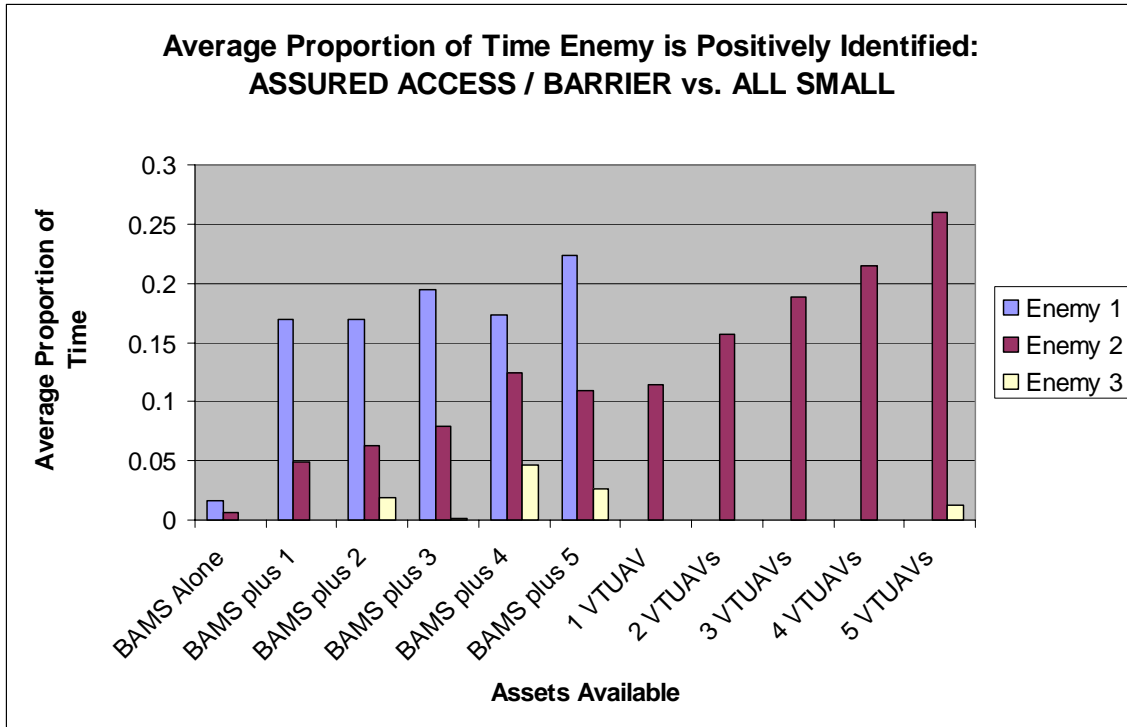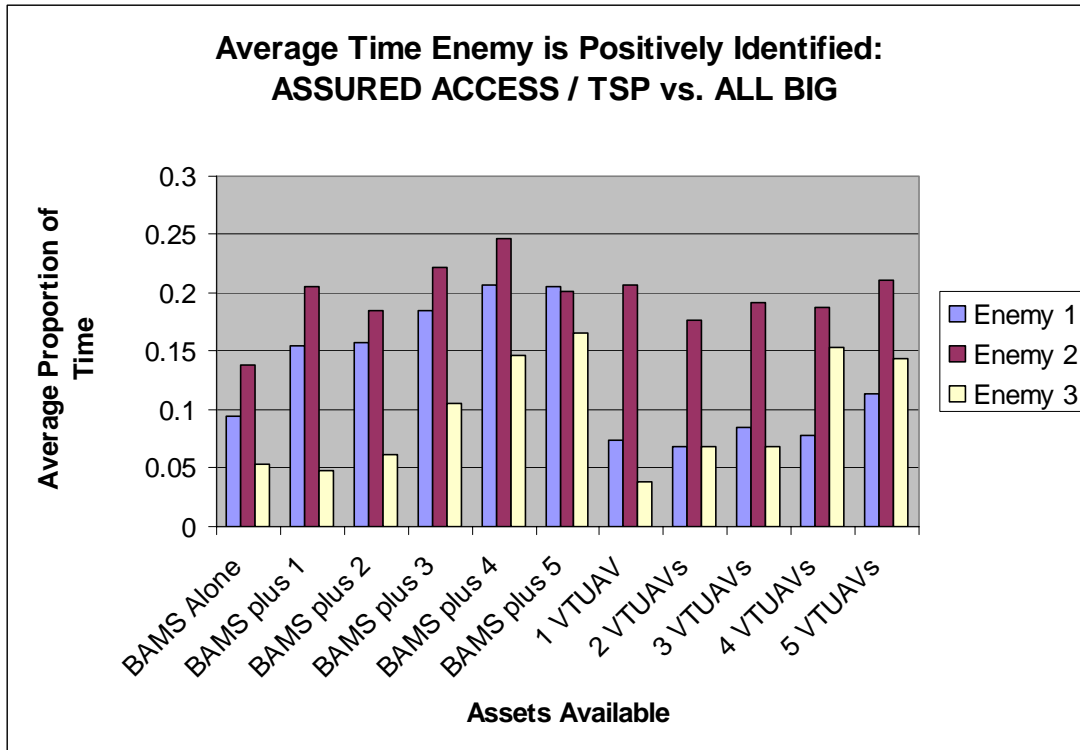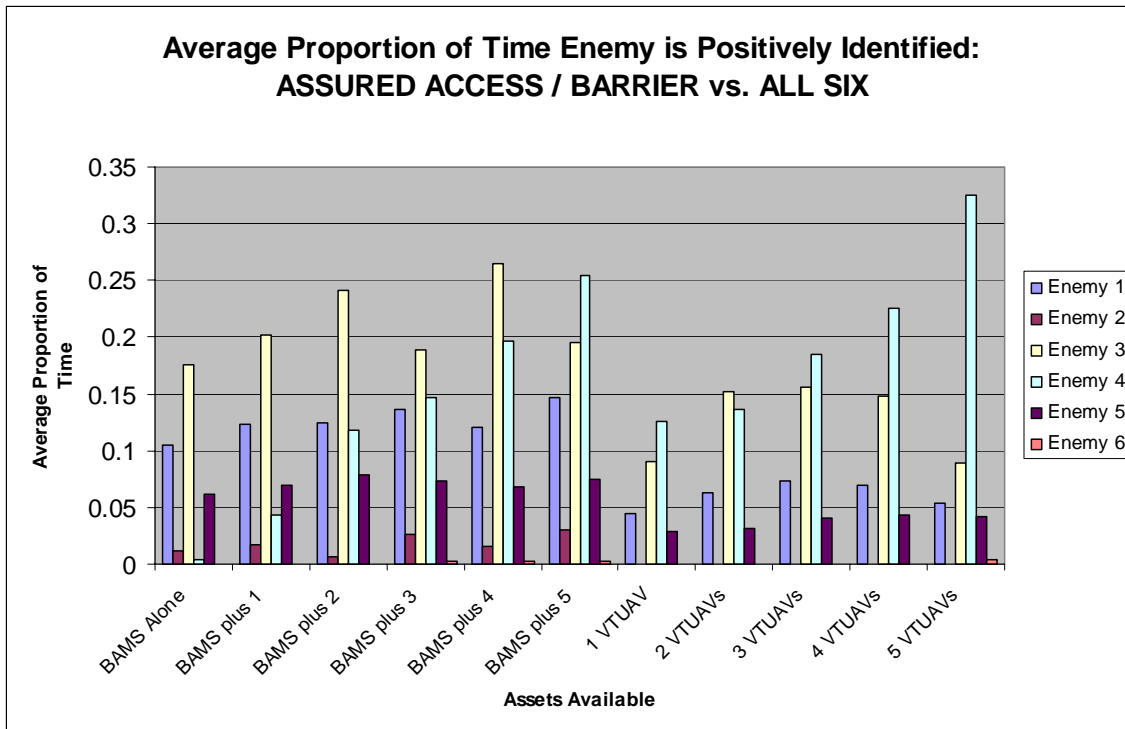
Figure 44: Average Proportion of Time Enemy is Positively Identified in Assured Access scenario with Blue "TSP" tactic and Red "All Six" maneuver scheme (best viewed in color)

Here again, all six enemy ships are tracked more often when BAMS is present. Without BAMS, the VTUAV combinations have a harder time tracking all contacts. In fact, no VTUAV combination manages to track Enemy 2 for any length of time at all.

As expected, the advantages of BAMS can be seen in terms of fishing vessels and neutral contacts. BAMS combinations are able to monitor these types of contacts for much longer portions of time than VTUAV combinations. Figure 45 shows the average proportion of time that Fishing vessels are positively identified in the Assured Access scenario when BAMS runs the "TSP" tactic and Red runs either the defensive "All Small," the aggressive "All Big," or the flooding "All Six" maneuver schemes.
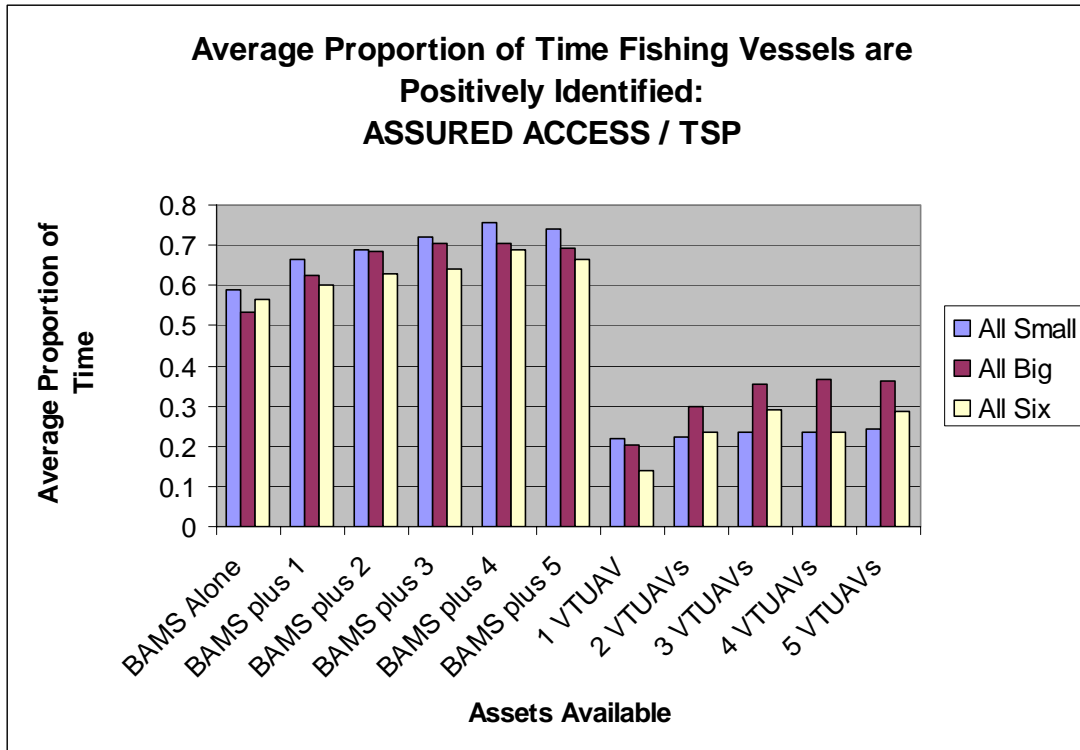
Figure 45: Average Proportion of Time Fishing Vessels are Positively Identified in Assured Access scenario with Blue "TSP" tactic and Red "All Small," "All Big," and "All Six" maneuver schemes (best viewed in color)

When BAMS is present, the proportions of time that these contacts are positively identified increase two or even threefold. Figure 46 shows similar results when Blue employs the "Barrier" tactic.
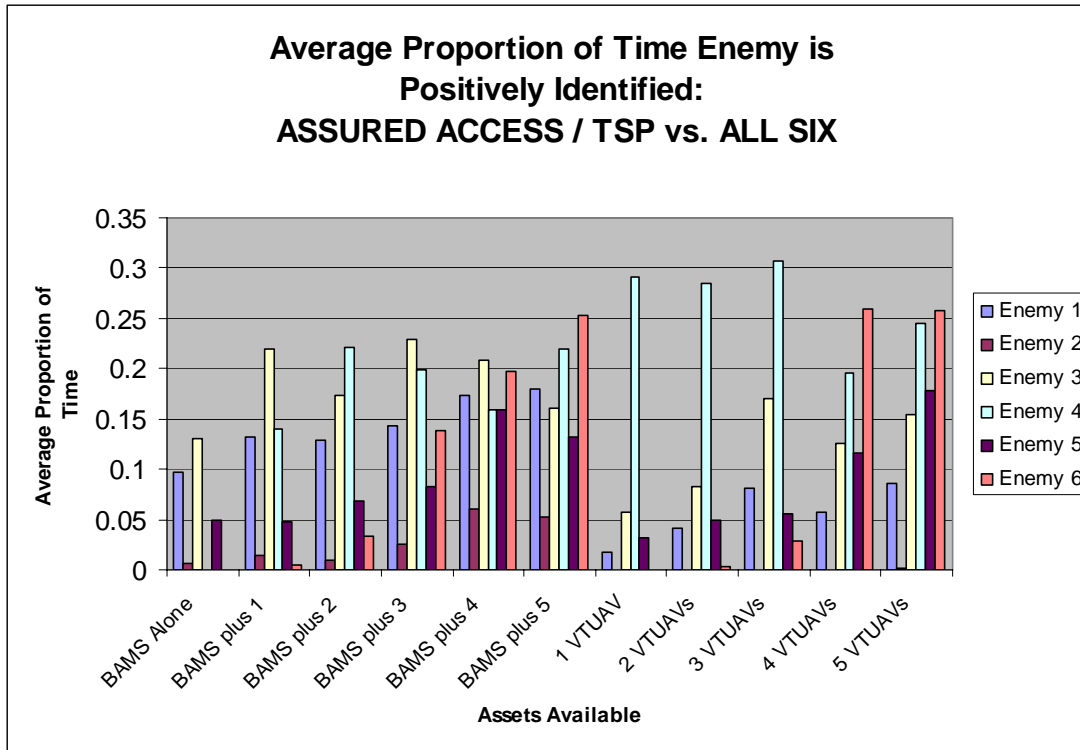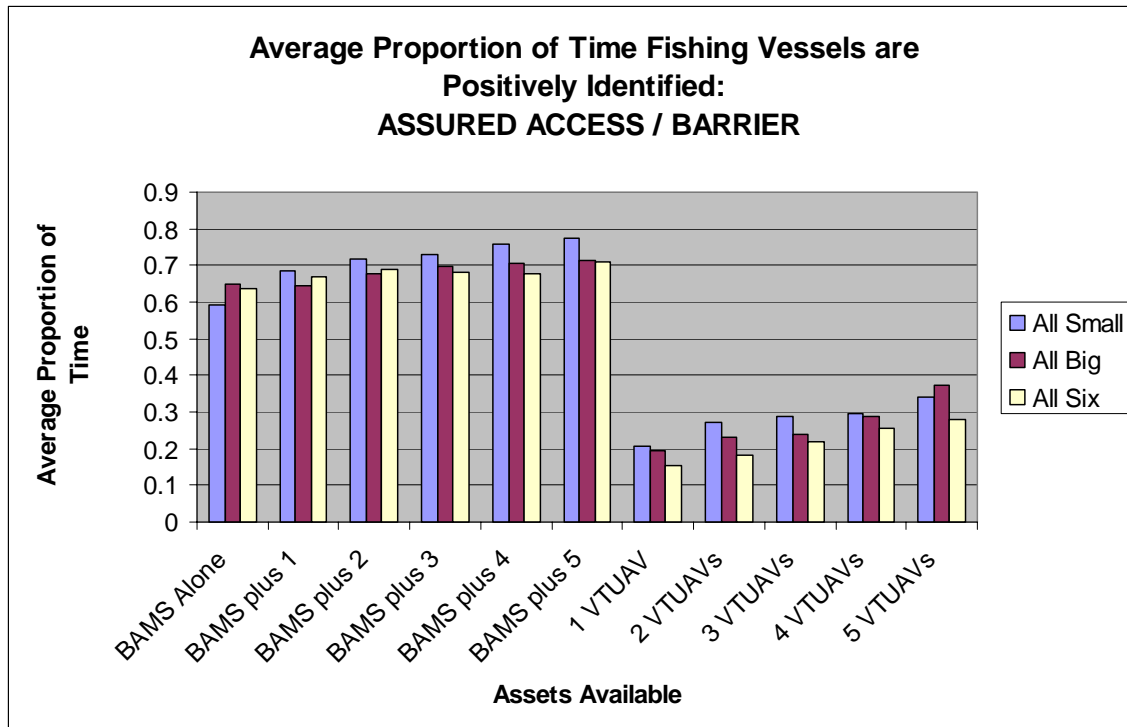
Figure 46: Average Proportion of Time Fishing Vessels are Positively Identified in Assured Access scenario with Blue "TSP" tactic and Red "All Small," "All Big," and "All Six" maneuver schemes (best viewed in color)

Likewise, there is a significant jump in maintaining full awareness of neutrals with BAMS. This is most likely attributed to the nature of the two types of UAVs. Again, the VTUAVs are "pouncers." Their small sensor ranges limit their ability to see all contacts and when they find enemy contacts, they tend to stick with them, ignoring neutrals.

BAMS, on the other hand, is a broad surveillance asset. It covers larger areas in shorter time periods and continuously revisits all contacts to update the broad picture. If there were even more enemies in these scenarios, one would expect that the VTUAVs would be even less effective, and the presence of BAMS would be even more important. Therefore, BAMS appears essential to keeping all contacts positively identified in the Assured Access

scenario regardless of whether the "TSP" tactic or "Barrier" tactic is employed by the Blue force.

C. ACCOUNTING FOR WEATHER IN ESTABLISHING THE COP

This study discusses the effects of varying BAMS' probability of classification to simulate the effects of high clouds. These high clouds impede BAMS' ability to make classifications with its EO/IR sensor. Classification probabilities for VTUAVs flying at lower altitudes are not affected. This experiment only deals with the Embargo scenario, the "TSP" tactic, and the Red "Combo" maneuver scheme.

Naturally, increases in classification probability should decrease the time required to make enemy classifications. This expectation is confirmed in Figure 47, which reflects increased cumulative probability of classification for BAMS alone.

Average Time to First Enemy Classification as BAMS Cumulative P(Classification) Increases: EMBARGO / TSP vs. COMBO
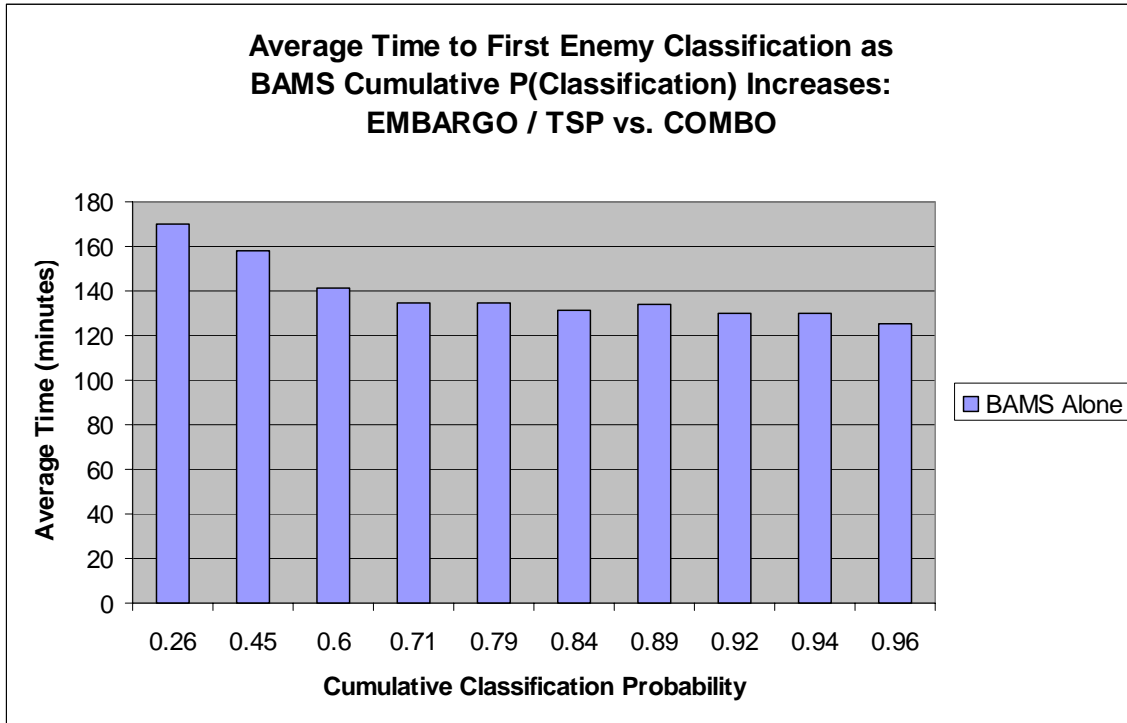
Figure 47 Average Time to First Enemy Classification as BAMS Cumulative P(Classification) Increases for the Embargo scenario with Blue "TSP" tactic and Red "Combo" maneuver scheme for the BAMS alone UAV combination (best viewed in color)

The average time to first enemy classification decreases as BAMS' cumulative probability of classification increases. The decrease seems to steady out after the cumulative probability increases past 0.60. However, when all possible UAV combinations are compared, the results are not the same. Figure 48 shows the results of varying the classification probability when more VTUAVs are available to operate with BAMS.
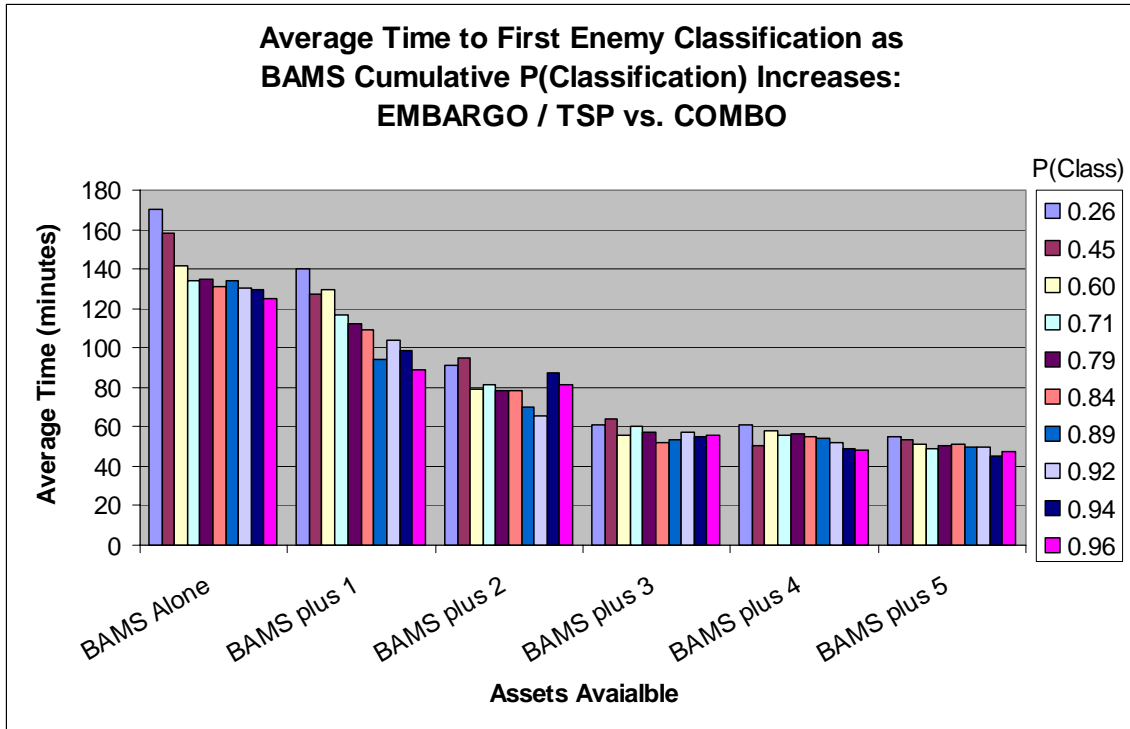
Figure 48: Average time to first enemy classification as BAMS cumulative P(Classification) increase for the Embargo scenario with Blue "TSP" and Red "Combo" tactic for BAMS plus additional VTUAVs (best viewed in color)

As the number of VTUAVs increases, the decrease in classification time is not consistent. The decrease in time settles out at the BAMS plus three combination, regardless of classification probability. Combinations with more UAVs compensate for decreases in classification probabilities.

Increases in classification probability should also consistently improve the proportion of time that UAVs can positively identify contacts. Modeling results are surprising in that no consistent improvement in the amount of time is shown over different UAV combinations.

This inconsistency is shown in Figure 49. Although there is improvement as the number of VTUAVs increases, the improvement within each UAV combination is variable.
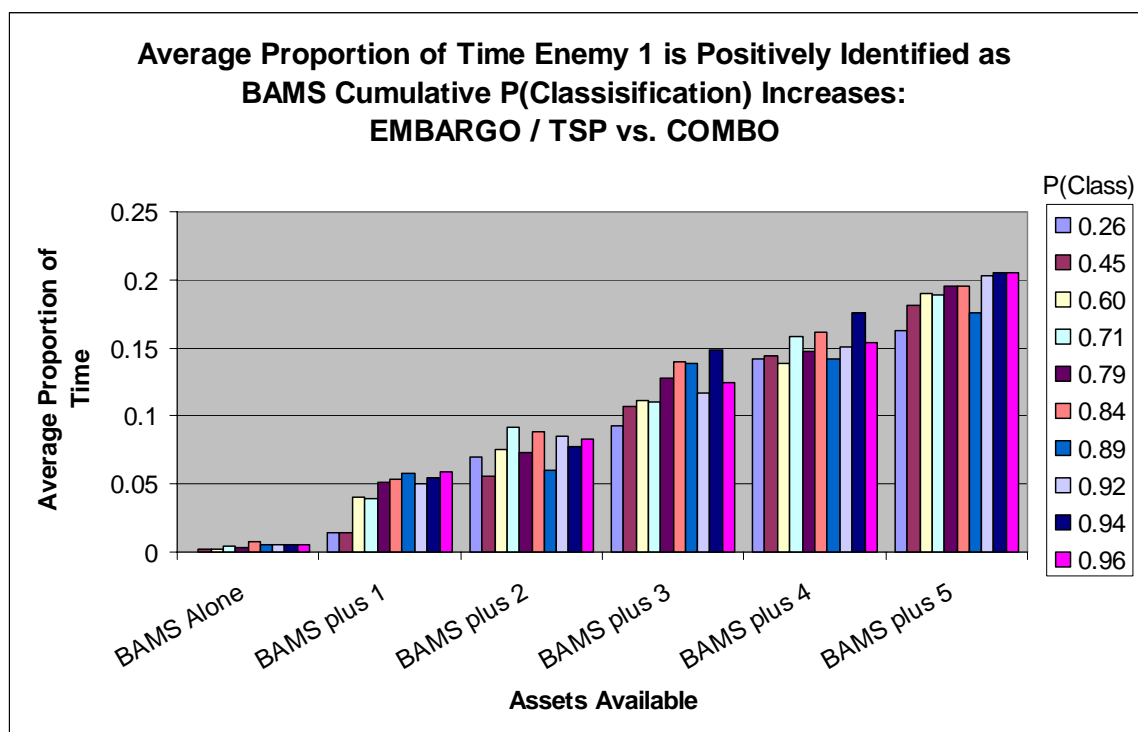
Figure 49: Average Proportion of Time Enemy 1 is Positively Identified as BAMS Cumulative P(Classification) Increases in Embargo scenario with Blue "TSP" tactic and Red "Combo" maneuver scheme (best viewed in color)

These inconsistencies stand out even more noticeably when the differences between the amounts of time that the first and second enemy ships are positively identified are presented in Figure 50.
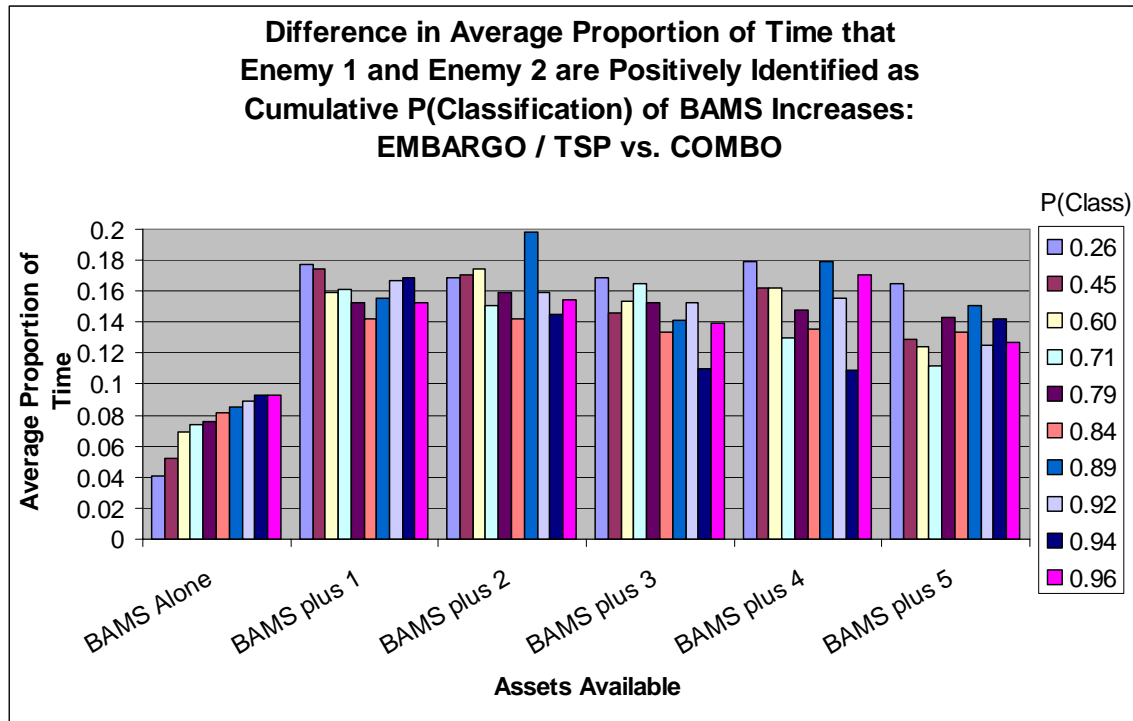
Figure 50: Difference in Average Proportion of Time that Enemy 1 and Enemy 2 are Positively Identified as BAMS Cumulative P(Classification) Increases in Embargo scenario with Blue "TSP" tactic and Red "Combo" maneuver scheme (best viewed in color)

Although the increase in time is consistent for the BAMS alone combination, every other combination exhibits high degrees of variability.

These data suggest that the probability of classification, as modeled by MANA, really does not have that much of a consistent effect on the amount of time that enemy contacts are positively identified. This might be partly due to the fact that MANA uses glimpse classification probabilities, which drive the cumulative probability of classification up to a value of 1.0 very quickly. In the future, a better way to model weather might be to change the cover or concealment values on different portions of the screen to simulate cloudy areas.

This might cause the probabilities to change more naturally.

V. CONCLUSIONS AND RECOMMENDATIONS

This research focuses on the effective use of unmanned aerial vehicles (UAVs) in the Navy's Surface Search and Control (SSC) mission, measured in terms of how UAVs help to maintain the Common Operational Picture (COP). To meet expectations, UAVs should help decision-makers by providing a picture that is on time, complete, and continuous. The results and analysis in Chapter Four measure these operational objectives with respect to the first time enemies are classified, the numbers of enemies that escape classification, the location of classification, and the duration of classification.

These measures provide specific operational insights into the numbers of UAVs, the types of UAVs, and the UAV tactics to employ. Several additional results about UAV numbers, tactics, and weather are also presented. All of these results are in the context of the 10,000 square nautical miles, dense maritime traffic, sparse enemy threat scenarios simulated and are subject to certain modeling assumptions. In addition to the operational insights, recommendations are given on areas deserving more research.

A. PRIMARY FINDINGS

There are four primary findings in this study. The first two pertain to the most effective numbers of UAVs. For the scenarios chosen, the best combination of UAVs is the Broad Area Maritime Surveillance (BAMS) UAV and two to three Vertical Take-Off UAVs (VTUAVs). However, small numbers of VTUAVs can do just as well, if not better, when

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they operate without BAMS versus when they operate with BAMS. The third finding deals with the most effective type of UAVs. Combinations of two or more UAVs that include BAMS tend to have advantages over those combinations without BAMS. These advantages include less average numbers of missed classifications and an increase in the proportion of time that all types of contacts are positively identified. The fourth finding deals with the best UAV tactics to employ. The study shows that the tactics that BAMS employs do not usually make that much of a difference. This is in large part due to its long detection range—i.e., no matter what its search pattern is, BAMS detects all surface contacts in the operational area.

In terms of numbers, this study provides two main results. For the scenarios modeled, the best UAV combination is BAMS plus two or three VTUAVs. This combination takes advantage of BAMS' long detection range and the "pouncing" ability of VTUAVs to find enemies the fastest. The results show that a "knee in the curve," in terms of UAV performance, exists with the BAMS plus two, or BAMS plus three VTUAV combinations. In other words, increases in performance are less significant with the addition of a third, fourth, or fifth VTUAV. This result is captured repeatedly by shorter times to first enemy classification on the COP and by any UAV, in both the Embargo and Assured Access scenarios. These results are also captured throughout different Red force and Blue force tactics combinations.

Secondly, in our model, sometimes smaller numbers of VTUAVs do as well, if not better, when they operate without

BAMS versus when they operate with BAMS. Times to first enemy classification in both the Embargo and Assured Access scenarios show that this is generally true regardless of Blue force tactic or Red force maneuver. This appears to be the result of the initial vectoring of the VTUAVs. When BAMS is present, the VTUAVs are drawn away from what happens to be a more beneficial course. This suggests that BAMS may provide minimal benefits with less numbers of UAVs.

In terms of the types of UAVs, combinations with multiple UAVs that include BAMS consistently outperform those combinations without BAMS. This is especially apparent in the average number of missed classifications as well as the average amount of time that each type of contact is positively identified. Combinations with BAMS always have fewer missed enemy classifications—if any at all. Combinations with BAMS also are able to track neutral contacts and fishing vessels for much higher average proportions of time than combinations without BAMS. This results in a clearer COP. It is reasonable to infer that the benefits of BAMS will be greater for scenarios with a greater number of enemy ships.

In terms of tactics, the performance of the UAVs is relatively insensitive to changes in BAMS tactics. This is definitely shown in results that compare times and locations of enemy classification for the Embargo scenario. It is also true in results that compare the proportions of time that contacts are positively identified in both the Embargo and Assured Access scenarios. This makes sense when the long detection range of BAMS is considered. Regardless of its position and vectoring, BAMS can still

detect all contacts in the operational area and alert VTUAVs to the presence of unidentified ships. Higher proportions of positive identification time can also be explained by the built-in characteristics of BAMS. Since BAMS is a relatively fast-moving platform and "breaks lock" from contacts in order to inspect other areas, it can still provide good contact coverage, regardless of its vectoring.

B. ADDITIONAL FINDINGS

Several secondary findings about UAV numbers, tactics, and weather can also be drawn from the results.

Single UAV employment consistently underperforms multiple UAV combinations. For example, a single VTUAV performs poorly in that it rarely, if ever, classifies enemy ships that take the coastal route in the Embargo scenario. With its relatively short detection range, it is harder for a single VTUAV to rapidly cover the whole region. BAMS also performs less effectively when operating alone. In the high-density traffic scenarios modeled, BAMS tends to get distracted with other contacts and does not "pounce" on them for long periods of time. Two assets tend to perform much better than one. Given the nature of both types of UAVs modeled, this result is to be expected and lends credibility to the model.

Sometimes BAMS tactics do affect results. For instance, the location of enemy classifications is affected by Blue force tactics in the Assured Access scenario. If the Blue force is under a tight timeline to identify everything along its path, then the "Barrier" tactic is better. This tactic focuses the search for identifications

along the Blue force track. This area must be screened in order to ensure a safe transit. The Blue "Barrier" tactic is also the most efficient in terms of the average number of misses in the Embargo scenario. If the Blue force is not time constrained and is more interested in an overall Maritime search, then perhaps the "TSP" tactic is more beneficial. This tactic allows the Blue force to probe an entire area faster.

The Red force "Coastal" maneuver increases difficulties for the Blue force in making an initial classification. However, the "Combo" maneuver scheme is most deleterious to Blue force performance in terms of the proportion of time Red forces are positively identified. It spreads out the Blue force and makes it harder to track multiple enemy contacts.

Finally, results from the advanced study of weather effects on BAMS indicate that reduced probabilities of classification seem to have inconsistent results. Part of this may be due to how MANA calculates probabilities of classification. In the model, the cumulative probability of classification accumulates quickly even for very low probabilities. Analysis on the same scenario with an increasing probability of classification shows the same "knee in the curve" around the BAMS plus two to BAMS plus three VTUAV point.

C.   ASSUMPTIONS AND LIMITATIONS

There are some additional assumptions and limitations with regard to this study that merit discussion. These

include the squad-like behavior of the VTUAVs, the effect of VTUAVs on BAMS, and VTUAV endurance.

The VTUAV agents sometimes operate as a squad, rather than individual agents. Despite completely different VTUAV squads in MANA, the VTUAV agents still exhibit slight tendencies to do exactly the same thing and cluster together. This tendency could certainly happen in real operational scenarios as decision-makers might fixate the attention of resources on newly classified contacts. However, the possibility exists that assets would be more dispersed. An increase in the ability of VTUAVs to operate independently could probably increase the effectiveness of any combination of UAVs that included multiple VTUAVs. However, since this increase in effectiveness would also apply to those situations with VTUAVs in the presence of BAMS, the relative performance of BAMS versus VTUAVs would most likely not change.

BAMS movement may not be completely realistic. The model sometimes shows that BAMS is inordinately affected by the presence of VTUAVs. Sometimes BAMS hesitates to over fly VTUAV positions. This hesitation would not normally occur since BAMS flies at such high altitudes. However, decreasing the effect of the presence of VTUAVs on BAMS would probably improve the performance of any UAV combination with BAMS and thereby enhance the results described earlier, rather than discredit them.

An implicit assumption is that unlimited VTUAV endurance does not significantly affect this study's results. Although VTUAV endurance is typically more than six hours (Klingbeil, 2004), VTUAV flight is continuous in the model. BAMS endurance is not a factor since it can

typically fly for more than 28 hours, much longer than the simulations ending time (NAVAIR 5.1.1, 2004). Endurance is not significant in the Assured Access scenario since only 5.1 hours of real time are simulated. However, it might be a factor for the Embargo results, which model 10.5 hours of real time. Since LCS packages are expected to consist of three VTUAVs per ship (Vertical Take-Off and Landing Tactical Unmanned Aerial Vehicle Installation Design Requirements, 2000), the analysis assumes that system redundancy in the Blue force makes up for any time gaps.

Because the movement of agents in this type of modeling is an abstraction, there is always some question of the model's veracity. In this case, however, the simulation still seems to provide reasonable results.

D.   OPERATIONAL IMPACT OF STUDY AND RECOMMENDATIONS

The conclusions from this study lend themselves to operational recommendations about the numbers of UAVs, the types of UAVs, and UAV tactics.

In terms of numbers, investments in more UAVs are warranted, but should not be overblown. More UAVs certainly seem to provide more operational capability, but there is a point of diminishing returns. In fact, the best results occur when BAMS operates with three VTUAVs and the poorest results are returned when a VTUAV operates alone. In addition, a consistent point of diminishing returns does exist at the two or three VTUAV point. A strong recommendation is to equip naval forces in scenarios similar to those modeled with enough capability that at least two VTUAVs can be operated at all times.

In terms of the types of future UAVs, this study may or may not validate the operational requirement for a BAMS UAV. Poorer performance of combinations with BAMS and less VTUAVs diminishes the importance of BAMS as a force multiplier. However, the effectiveness of BAMS with higher numbers of VTUAVs advocates the use of BAMS. In addition, BAMS' benefits in terms of reducing the number of leakers, and providing overall coverage may outweigh all other results. A valid recommendation is to pursue the procurement of BAMS, but to augment it with at least two other cooperative VTUAVs.

Finally, in terms of tactics, this study suggests that with respect to BAMS, tactics are less important than the presence of BAMS itself. For the most part, results with changes in both enemy and friendly tactics seem to provide similar results. A valid recommendation is to emphasize studies with other scenarios to see if this is always the case.

E. FOLLOW-ON RESEARCH

This thesis provides many opportunities for follow-on research. Some of these opportunities include:

- Further analysis of the impact on the location of enemy classifications with respect to different UAV combinations.

- Studies on the impact of variations of revisit time requirements. Future studies could vary the amount of time that classified contacts spend in "stealth mode" in order to study the impact of longer or shorter revisit time requirements for different types of contacts.

- More data farming across all UAV parameters to include speed, endurance, sensor ranges, etc. This study assumes that all UAVs maintain constant speed and are not affected by endurance limitations. Endurance would reduce the availability of VTUAVs over a given period of time.

- Studies into the effects of communications latency and reliability. This study assumes 100% reliability and no latency in all communications between all UAVs and ships. MANA provides a readily accessible capability to change these parameters on communications links.

- Further data analysis on weather effects. Due to time constraints, it has not been possible to analyze all of the data collected for this study in regard to weather effects. Separate data has been collected on the Embargo and Assured Access scenarios when the VTUAV probabilities of classification are modified, in addition to the BAMS probabilities of classification. These simulation runs simulate the presence of low altitude and/or high altitude cloud layers and are available for more research. Another option to further study the effects of weather would be to create different areas of clouds on the scenario maps. Clouds could be simulated by having the concealment levels of ships increase while they travel through these cloudy areas. Many different cloud configurations could be used to gather more data.

- Further analysis on more complicated types of tactics. This study limited tactical changes primarily to changes in direction. Future analysis on changes in Red force tactics due to counter-detection, for example, with

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varying speed and propensities to move toward other
contacts, would be valuable.

APPENDIX.   GHMD TACSITS

This appendix provides the Naval Air Systems Command (NAVAIR) approved Tactical Situations (TACSITS) used to create the scenarios modeled by the author. These TACSITS are provided by Mr. Ed Romero, NAVAIR 5.1.1. As of the time of this publication, the concept of operations (CONOPS) document for Global Hawk Maritime Dominance (HALE, 2004) is still in draft version. These documents are presented as received, with some information still to be determined.

In this study, the Embargo scenario combines the Embargo and Surface Warfare (SuW) TACSITS. The Assured Access scenario combines the Indications and Warning (I&W) and Intelligence, Surveillance, and Reconnaissance (ISR) TACSITS.

EMBARGO TACSIT

1) Introduction/Objectives

Smugglers are using territorial waters and merchant ship traffic to avoid prosecution. An overt naval presence would tip off the smugglers, and there is no cohesive, accurate surface picture of shipping.

GHMD's objective is to support the common operational picture and provide classification and identification to the greatest extent possible using the ELINT and imaging sensors.

The environment is characterized as requiring operations both day and night, with conditions being generally clear with some high clouds. The operational area is characterized as high shipping density.

2) Roles and Responsibilities

GHMD will be operating at altitude, beyond detection capability of the smugglers. High altitude flight profile is expected to prevent detection.
- a. **OPCON:** to Fleet commander
- b. **TACON:** to Fleet or SAG commander
- c. **Mission Commander (MCE):** Sensor control

3) Architectural Views (Operational Views, System Views, Tech Views)
- a. **Comm Plan:** Provide SA to SAG of all surface threats. Provide data to both "acting Fleet and SAG commanders, if possible.
- b. **Sensor Employment Plan:** Focused surveillance (MWAS, ISAR, MMTI, SAR, EO, ELINT)
    - i. Continuous surface plot
    - ii. Track, Classification & Identification
    - iii. ELINT support
- c. **Pipes and Products:**
    - i. LOS: CDL direct down link to CV/Ship
    - ii. BLOS: SATCOM, if available
- d. **Data Processing:**
- e. **Data Dissemination:**

4) Recap/Timeline View:

SURFACE WARFARE (SUW) TACSIT

1) Introduction/Objectives:

The region is characterized by ongoing border disputes between two adjacent countries. There is the potential for general was with possible WMD escalation. A red SAG is operating near the Sea Lines of Communication (SLOCs). The SAG threatens vital supply convoys and must be neutralized.

US mission is to establish maritime supremacy, and halt or defeat advancing forces. The GHMD mission is to search, detect, identify, and track all SAG elements. If necessary, GHMD may be required to provide targeting data for various SAG elements for subsequent prosecution by other assets.

The environment requires both day and night operations under partly cloudy conditions. The maritime environment encompasses both Open Ocean and Littoral waters, with high-density merchant shipping traffic in the area.

2) Roles and Responsibilities: GHMD will operate in an altitude sanctuary to counter the possible SAM threat.
   a. **OPCON:** to Fleet Commander
   b. **TACON:** to Tactical Support Center. TSC will vector GHMD to ISAR range for target classification
   c. **Mission Commander (MCE):**
3) Architectural Views (Operational Views, System Views, Tech Views):
   a. **Comm Plan:** Link 16 may be used to pass target data directly to shooter.
   b. **Sensor Employment Plan:** MWAS, ISAR, MMTI, EO, IR, ELINT. ELINT monitors SAG target acquisition & fire control radars. EO/IR to confirm identification. MWAS tracks SAG elements, ELINT builds SAG OOB.
   c. **Pipes and Products:**
   d. **Data Processing:** Radar, ELINT, ISAR, and EO/IR data fused at the TSC (to the greatest extent possible)
   e. **Data Dissemination:**
4) Recap/Timeline View:

INDICATIONS & WARNING (I&W) TACSIT

1) **Introduction/Objectives**

A sudden flare up of increased operations in the region has characterized the area. A potential for aggression/hostilities exists.

The US objective is to maintain sea control of the OPAREA. Strike operations may need to be conducted, if required. GHMD's objective will be to support the common operational picture and provide Indications and Warning of any impending threat/hostile action.

The environment is characterized by party cloudy conditions with the requirements to provide both day and night operations. The maritime environment may be described as "congested".

2) **Roles and Responsibilities:** The AV can be assumed to be operating in international airspace at all times at altitudes greater than 50K and at least 25 nautical miles from the shoreline.

   a. **OPCON:** to Fleet Commander / Carrier Strike Group Commander
   b. **TACON:** to Expeditionary Strike Force Commander
   c. **Mission Commander (MCE):** Focus all I&W sensors on tactical problem
3) **Architectural Views (Operational Views, System Views, Tech Views):** It can be assumed that a high revisit rate will be required for time critical targets. Continuous tracking of the surface picture (to the greatest extent possible) is desired
   a. **Comm Plan:**
   b. **Sensor Employment Plan:** MWAS, ISAR, MMTI, SAR, EO, IR, ELINT. Conduct surveillance of naval forces in the area and monitor any buildup of forces.
   c. **Pipes and Products:** Sensor data can be assume to be disseminated via satellite (SATCOM). CDL is assumed to be dedicated to ASW forces on station.
   d. **Data Processing:** Image exploitation facilities and the transmission of data and the corresponding throughput and latency must be considered

      e. Data Dissemination: Sensor data can be assume to be disseminated via satellite (SATCOM)

4) Recap/Timeline View:
      a. Pre-Flight:
      b. Flight Execution:
      c. Post-Flight:

INTELLIGENCE, SURVEILLANCE, RECONNAISSANCE (ISR) TACSIT

1) Introduction/Objectives:

The region is characterized by ongoing border disputes between two adjacent countries. There is the potential for general was with possible WMD escalation.

US mission is to establish maritime supremacy, and halt or defeat advancing forces. GHMD's role is to provide I&W for MMA and the DDGs and to maintain the surface picture with sustained multi-sensor surveillance. Periscope detection is desired, if possible with the current radar.

The environment is characterized by night operations, with a broken ceiling art 10 Kft, 3 foot waves, and a moderate-to-high shipping density. Undetected diesel submarine activity is suspected. USN DDGs and Carrier Strike Groups are operating in the area.

2) Roles and Responsibilities:
   a. **OPCON:** to Fleet Commander
   b. **TACON:** to Carrier Strike Group Commander
   c. **Mission Commander (MCE):**
3) Architectural Views (Operational Views, System Views, Tech Views):
   a. **Comm Plan:** Link 16 and SATCOM to ship(s)/aircraft
   b. **Sensor Employment Plan:** MWAS, ISAR, MMTI, EO, IR, ELINT. Radar flooding may be used to deter/complicate SS targeting while building surface picture.
   c. **Pipes and Products:** Link with DDG, Fleet Commander and P-3 (if possible)
   d. **Data Processing:**
   e. **Data Dissemination:**
4) Recap/Timeline View:
   a. **Pre-Flight:**
   b. **Flight Execution:**
   c. **Post-Flight:**

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